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# Solar Thermal Technology

## *Annual Evaluation Report Fiscal Year 1982*

### Volume II: Technical

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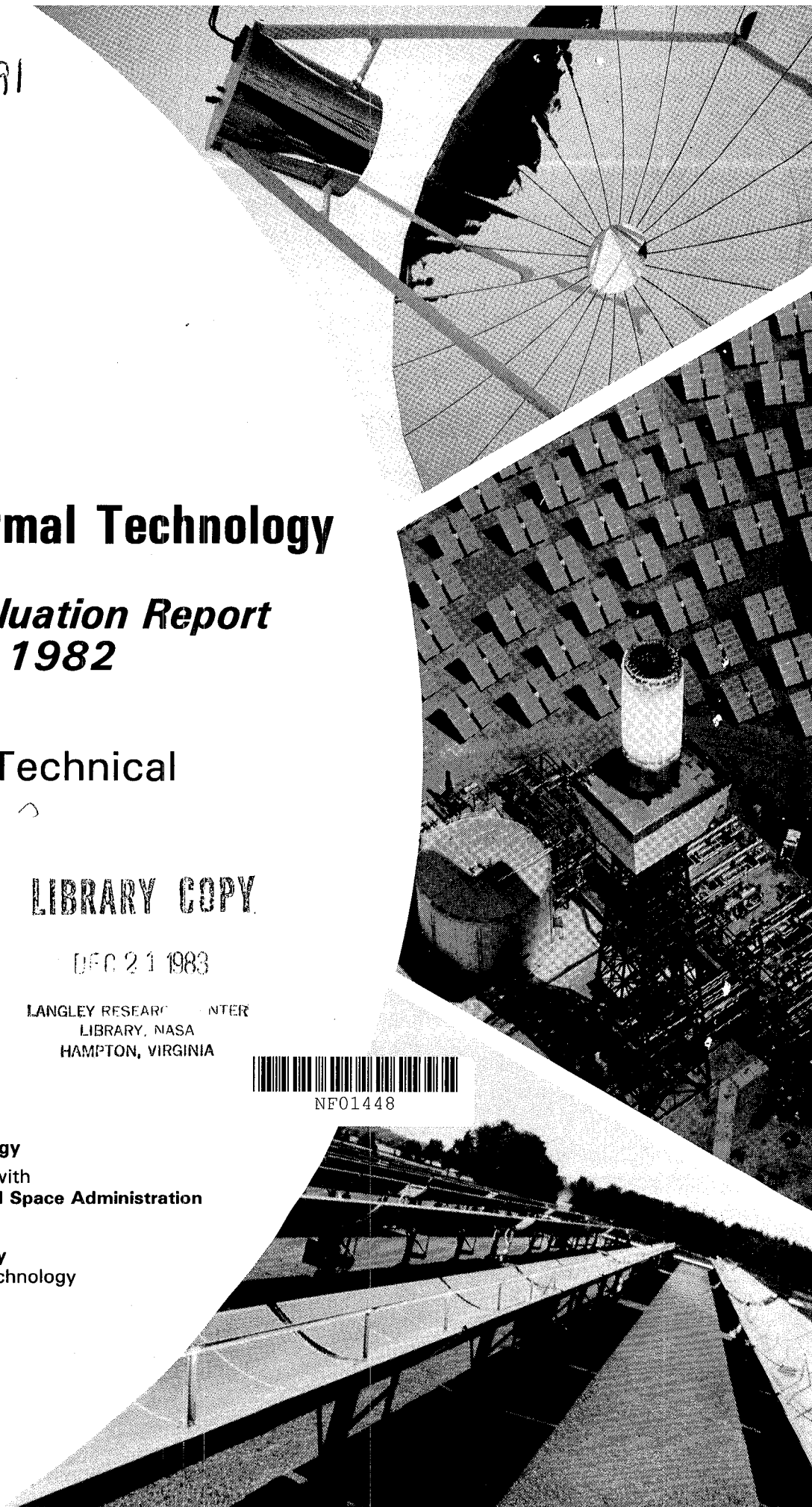


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Prepared for  
**U.S. Department of Energy**  
Through an Agreement with  
**National Aeronautics and Space Administration**  
by  
**Jet Propulsion Laboratory**  
California Institute of Technology  
Pasadena, California

JPL Publication 83-60

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## ABSTRACT

This report, which is divided into two volumes, documents the accomplishments and progress of the U.S. Department of Energy Solar Thermal Technology (STT) Program during FY 1982, covering the period from October 1, 1981 to September 30, 1982. The focus of the STT Program is research and development leading to the commercial readiness of three primary solar thermal concepts: the central receiver, parabolic dish, and parabolic trough. To a lesser extent, the hemispherical bowl and salt-gradient solar pond are also being studied. This development effort is complemented by numerous research and planning activities.

Volume I, the Executive Summary, contains a brief description of each technology and highlights of the fiscal year's technical activities. Volume II details FY 1982 accomplishments and includes a bibliography, list of contacts, acronyms, and definition of terms relevant to solar thermal technology and the STT Program.



## ACKNOWLEDGMENTS

The work described herein was carried out by various research organizations and government laboratories, including the Jet Propulsion Laboratory, Sandia National Laboratories, and the Solar Energy Research Institute, their contractors, and supporting universities for the U.S. Department of Energy directly and through its field operation offices in Albuquerque, New Mexico, and San Francisco, California. This report was coordinated by the STT Program's Technical Program Integrator at Sandia National Laboratories in Livermore, California; it was published by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration (NASA Task RE-152, Amendment 342; DOE-Sandia/NASA Interagency Agreement No. 92-9458).

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## SECTION I

### INTRODUCTION

#### A. THE PROGRAM

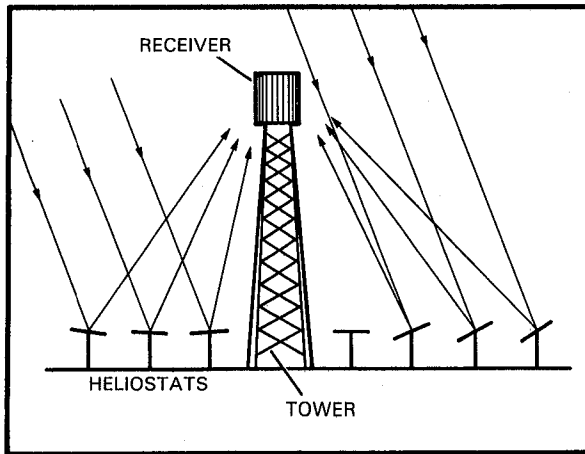
Solar thermal energy systems convert the sun's radiant energy into basic heat energy ranging in temperature from 100 to 1700°C (approximately 200 to 3000°F). This heat can be used for generating electric power for process heat applications or, using endothermic chemical reactions, for production of fuels and chemicals from renewable resources. During FY 1982, the U.S. Department of Energy's Solar Thermal Technology Program continued to develop five solar energy conversion concepts: four types of concentrating collectors and salt-gradient solar ponds. The concentrating collector concepts (Figure 1-1) include central receiver systems (employing heliostats), parabolic dishes, parabolic troughs, and hemispherical bowls. These collectors use reflecting mirrors to focus or concentrate the sun's rays onto a receiver where the radiant energy is converted into medium- to high-temperature heat. Salt-gradient solar ponds rely on density variations in the water to suppress convection, enabling the pond to collect and store heat at temperatures up to 100°C (212°F). These five concepts are in varying stages of development.

The Solar Thermal Technology (STT) Program utilizes an efficient organization and management framework for advancing the technology of each system concept. This organization, shown in Figure 1-2, encompasses two major programs: (1) the Research and Technology Program, which conducts research and advanced development as well as technology development of solar thermal materials, components, and subsystems, and (2) the Systems Test and Evaluation Program, which builds, tests, and evaluates the performance of subsystems and systems. The Planning and Assessment element conducts the program's overall planning and evaluation and provides a coordinating link among the various program elements.

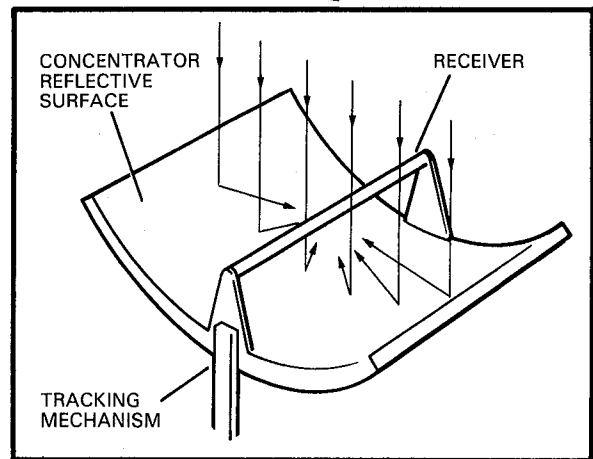
The rationale for the federal solar thermal program is based on a variety of benefits resulting from the research and development (R&D) of solar thermal technology as well as the fact that the inherent risks make industrial sponsorship of this R&D unlikely. Dwindling supplies of nonrenewable energy resources and the potential economic and political instability caused by U.S. dependence on these resources require the development and deployment of alternate energy technologies. Solar thermal technologies can provide a significant contribution to this effort because their primary impact will result from the displacement of the most used and expensive resources -- oil and natural gas, which currently supply over 75% of the nation's energy requirements.

#### B. GOALS AND OBJECTIVES

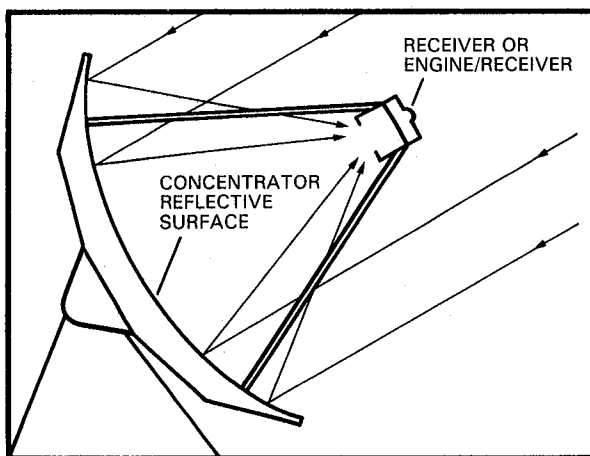
The goal of the STT Program is to establish the technology base of solar thermal energy, thereby allowing the private sector to produce and deploy systems capable of meeting the range of energy demands typical of U.S. industry and utilities. This goal focuses on developing the materials, components, subsystems, and processes capable of meeting specific energy cost targets. The program, therefore, emphasizes research and development to increase system efficiency and reliability and to reduce system cost.



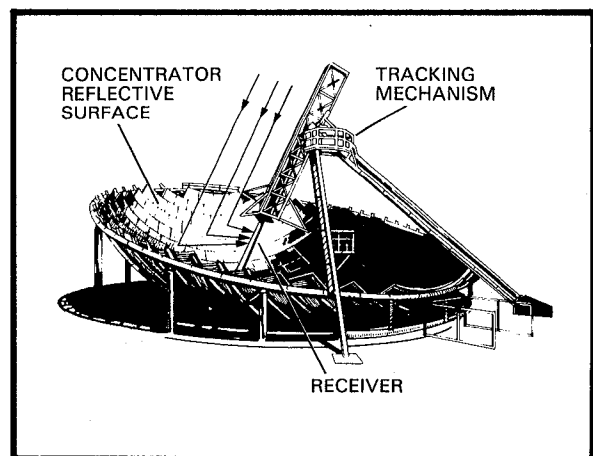
CENTRAL RECEIVER



PARABOLIC TROUGH



PARABOLIC DISH



HEMISPHERICAL BOWL

Figure 1-1. Solar Thermal Energy Concentrating Collector Systems Concepts

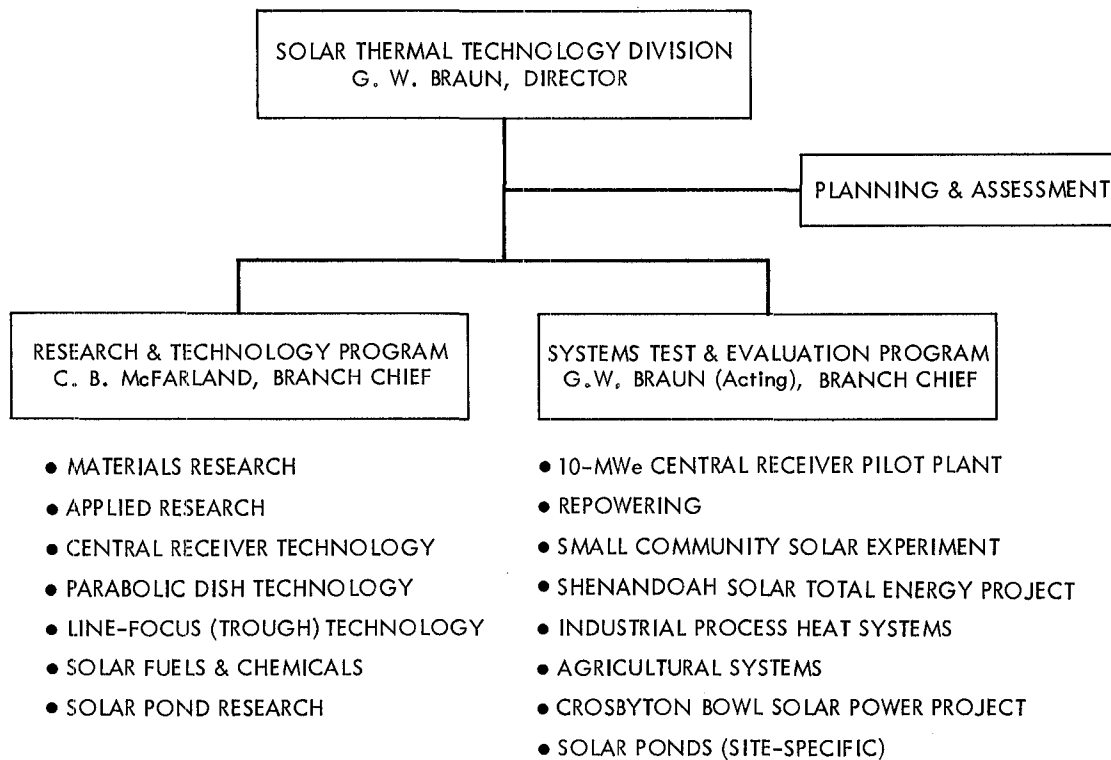


Figure 1-2. Solar Thermal Technology Program Structure

To achieve this goal, the following objectives have been defined:

- (1) Complete the R&D required to support the near-term (1983-1985) and mid-term (1985-1990) needs of industry and utilities for electric, cogeneration, and process heat applications.
- (2) Conduct the R&D needed to expand the technology base of solar thermal energy into new high-risk, high-payoff solar concepts, including high-temperature process heat applications and the production of fuels and chemicals from renewable resources. Research and technology development for fuels and chemicals production is the principal long-term (beyond 1990) objective of the Solar Thermal Technology Program.

Industry and utilities will conduct the development required to demonstrate technological and commercial readiness of solar thermal systems.

Energy cost targets have been established for electric and industrial process heat (IPH) applications of solar thermal technology. The mid-term energy cost targets reflect a value that is derived from the cost of competing conventional energy systems in the 1990s. These cost targets are deemed

achievable at collector production volumes of about 1,000,000 m<sup>2</sup>/year/factory.<sup>1</sup> The long-term energy cost targets are deemed achievable five years later.

R&D activities are planned or are underway to meet each program objective. To meet the near-term needs of industry and utilities, the STT Program will operate and evaluate installed system experiments, complete repowering system designs, and develop advanced central receiver technologies for bulk electric applications.

To address mid-term needs, the program will sponsor R&D for dispersed electric applications and high-temperature (greater than 600°C or 1112°F) process heat applications. Activities include system designs, materials research, laboratory experiments, and solar experiments for receivers using liquid, gas, and solid particle thermal transport media. Similar activities for thermal storage technology development are also planned.

Finally, the long-term program objective will be addressed by conducting R&D on new, high-risk, high-payoff solar concepts. Planned activities initially will emphasize fuels and chemicals production from renewable resources, including thermochemical hydrogen production by means of water splitting. To establish the technology base for additional solar fuels and chemicals concepts, activities are planned in four areas: (1) exploration of direct flux reactors, (2) thermal materials research for receivers and storage, (3) technology development for receivers and process development, and (4) system studies to address solar process interfaces.

The STT Program will minimize R&D costs by using the existing solar thermal technology base to the greatest possible extent. Collector, receiver, and storage technologies developed for electric, cogeneration, and process heat applications will be extended for use on fuels and chemicals applications wherever feasible. The program will also assure the transfer of the technology base to the private sector through workshops, meetings, and publication of reports.

The strategy for meeting the program objectives is to pursue government-sponsored and cost-shared R&D aimed at achieving a sufficient level of technical maturity for the various solar thermal technologies so that decision makers within the private sector will find acceptable risks should they choose to manufacture, market, or use the technologies. These activities are carried out through the technical direction of the U.S. Department of Energy (DOE) and its network of national laboratories, who work with private industry under contract to, or in cost-shared partnership with DOE and its field management organizations.

Contained in the balance of this report are the description, objectives, and FY 1982 accomplishments of all elements of the Solar Thermal Technology Program. Also included, where appropriate, are the issues and technical barriers that still need to be overcome before various segments of the program can be turned over to private industry for final development and commercialization.

---

<sup>1</sup>This production volume corresponds to the annual construction of solar plants that have a total output of 600 MWt or 200 MWe.

## SECTION II

### CENTRAL RECEIVER TECHNOLOGY

FY 1982 efforts to further develop central receiver technology emphasized heliostat performance/requirements optimization, sodium-cooled receiver evaluation, solid particle receiver investigation, and molten salt thermal energy storage design and development. Systems experiments and analyses in the central receiver area included the 10-MWe Central Receiver Pilot Plant near Barstow, California; the Small Solar Power Systems Project near Almeria, Spain; and the Molten Salt Electric Experiment under construction at the Central Receiver Test Facility in Albuquerque, New Mexico.

#### A. COMPONENT TECHNOLOGY DEVELOPMENT

##### 1. Heliostat Technology Development

Heliostats typically represent 50% or more of the capital cost of a central receiver system. Hence, much work has been done to lower heliostat costs. Future work will be directed toward metal membrane designs and development of polymeric materials, which are expected to reduce heliostat costs to at least 50% below current second-generation designs.

a. Heliostat Performance/Requirements Optimization. Following the FY 1981 Second-Generation Heliostat Development Program, two study contracts were conducted to optimize heliostat performance and requirements in an effort to reduce heliostat costs. Martin Marietta Corporation and McDonnell Douglas Astronautics Company completed these studies using their second-generation heliostat design as a baseline. Both contractors identified system-level specification changes, as well as heliostat changes and minor environmental changes, that can significantly reduce heliostat costs. The most significant conclusions and recommendations from these studies are summarized below.

- (1) Heliostat Strength. It is more cost effective to design heliostats for strength rather than for stiffness and also to design them to design-code wind speeds and pay for repair of damage caused by severe winds rather than design and manufacture the heliostats to withstand the severe winds. Furthermore, when heliostats are redesigned for strength, the optimal mirror area increases significantly.
- (2) Heliostat Size. When the contractor's baseline heliostat is redesigned for strength rather than for stiffness, the optimal mirror area increases significantly. Figure 2-1 shows a comparison of heliostat sizes.
- (3) Wind Angle of Attack. The 40 m/sec (90 mi/h) wind horizontal angle of attack can be reduced from 10 degrees to 6.5 degrees to match measured data.

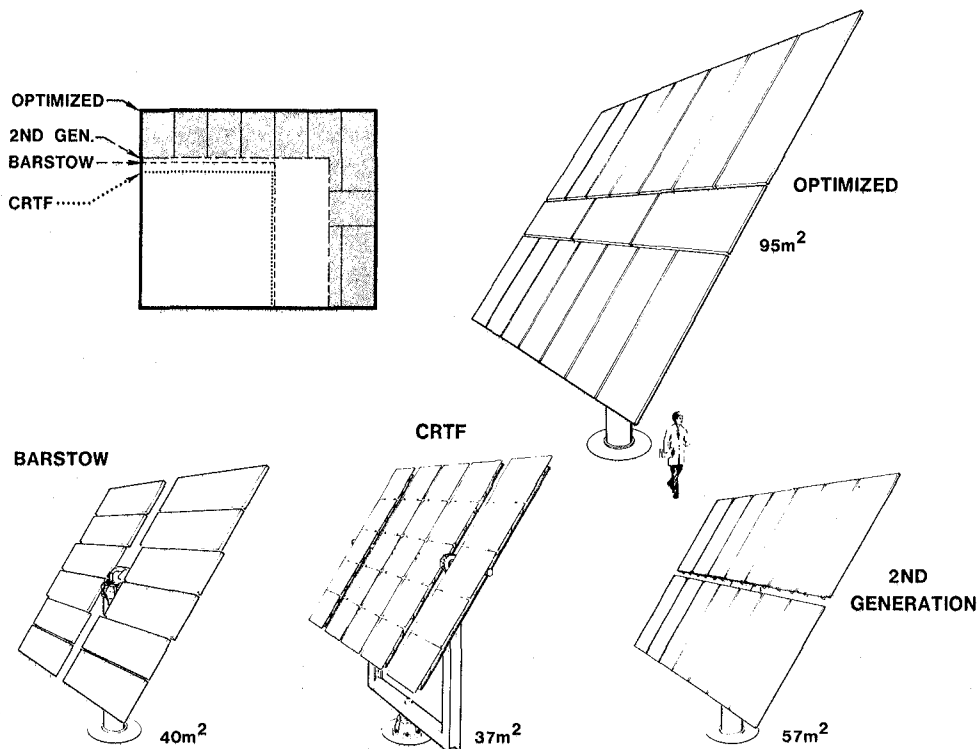


Figure 2-1. Heliostat Size Comparison

- (4) Pointing Accuracy and Beam Quality. If heliostat pointing or beam quality errors are increased by a factor of two or three for an entire field of heliostats, the cost of the energy collected is not reduced because the lower cost of the heliostats is offset by the additional spillage on the receiver. However, if heliostats with varying pointing accuracies were installed in the same field, costs could be reduced by using less accurate heliostats close to the tower.
- (5) Wind Shielding. Wind tunnel test data indicate that when heliostats are in an operational position, there is an appreciable reduction in wind loads for heliostats located away from the edge of the field. For a 50-MWe field, the moment reduction is 79%. If this moment reduction is verified for a field of heliostats, lower-cost foundations and pedestals can be used for interior field locations. Wind tunnel test results do not indicate use of wind shielding when heliostats are in a horizontal stow position.
- (6) Temperature Range. A reduced operational temperature range is possible for the sites studied. This smaller range can benefit mirror modules that defocus with temperature changes.

b. Second-Generation Core-Style Modules. The solar mirror module development effort has focused on solving the problem of water corrosion of silver surface of glass mirrors. All but one of the

second-generation mirror module designs have eliminated that problem. Two of the designs, however, showed evidence of water damage to core material (not the mirror), thereby weakening the module structure. These two designs have been replaced with concepts that do not have cores. (Refer to Section II.B.1.a for a discussion of mirror module silver corrosion.)

c. New Boeing Mirror Module Design. Adhesives used in outdoor structural designs have two fundamental limitations: They are affected by environmental aging and cannot easily be inspected for quality of adhesion without destroying the bonds. Boeing Engineering and Construction was contracted to design and build a mirror module that uses no adhesives in construction other than the adhesive used for laminating the mirror. The final Boeing design used push-in-place fasteners instead of adhesives and other off-the-shelf parts with thin glass laminated to thicker glass mirrors. Testing began in the summer of 1982 and is continuing. Costs for this design have been estimated to be comparable to those for the McDonnell Douglas second-generation heliostat mirror module.

d. Heliostat Mirror Cleaning System. Early in FY 1982, Foster Miller Associates began design of a system to clean glass mirrors on heliostats. The design was near completion at the end of FY 1982. In this design, a system is mounted on a flatbed truck that remains stationary as pairs of vertical spray bars and vertically oscillating brushes move past the mirror surface. Controls sense the distance from the mirror, mirror edges, and protruding heliostat drive motors and provide an independent vertical reference. Only one person will be required to operate the system, which carries enough water for a continuous 4-hour shift. The system reduces the problems associated with current washing techniques, such as the need for multiple operators, the use of chemicals for effective cleaning, and short nonstop shifts.

## 2. Receiver Technology Development

a. Molten Salt Receiver Development. Parallel advanced molten salt receiver development efforts conducted by Babcock & Wilcox and Foster Wheeler during FY 1982 involved (1) the development of system-level requirements and specifications for a receiver subsystem, (2) the design and costing of a 320-MWt receiver subsystem, and (3) the development of shop fabrication processes, particularly for the modular receiver panels. The goal was to identify and resolve all important technical uncertainties concerning the receiver subsystem. Significant progress has been made in addressing the critical issues raised at the start of work, as well as those identified during implementation of the contracts in FY 1982. Both contracts specified receiver designs operating with molten nitrate salt (60%  $\text{NaNO}_3$  and 40%  $\text{KNO}_3$  by weight) working fluid and sized to provide 320 MWt at an insolation level of  $950 \text{ W/m}^2$  with nominal receiver fluid inlet and outlet temperatures of  $290^\circ\text{C}$  ( $554^\circ\text{F}$ ) and  $565^\circ\text{C}$  ( $1049^\circ\text{F}$ ), respectively.

Significant parameters of the receiver design configurations selected by Babcock & Wilcox and Foster Wheeler are compared in Table 2-1. The Babcock & Wilcox "quad cavity" design (Figure 2-2) has 98 receiver panels arranged in



Table 2-1. Comparison of Advanced Molten Salt Receiver Designs [320 MW Receiver Thermal Power Rating, 565°C (1049°F) Outlet Temperature]

Significant Parameter	Foster Wheeler	Babcock & Wilcox
Initial Concept Basis	McDonnell Douglas/Sierra Pacific Power Repowering	Martin Marietta/Arizona Public Service Repowering
Final Concept	"Omega Cavity" (single north-facing cavity)	"Quad Cavity" (four cavities)
Heliostat Field	North	Surrounding
Tower Height, m (to base of receiver)	185	155
Total Height, m (tower and receiver)	235	202.5
Receiver Characteristics:		
Number of Panels	20	98
Panel Height (overall), m	28.4 (all panels)	15.7 to 26.1
Panel Width, m	2.44 (all panels)	0.81 (54) or 1.22 (44)
Active Surface Area, m <sup>2</sup>	1256	2078
Maximum Flux, MW/m <sup>2</sup>	0.66	0.49
Flow Control Zones	2	4
Panels per Zone	10	22 (2) or 27 (2)
Receiver Weight, kg	1.34 x 10 <sup>6</sup>	2.36 x 10 <sup>6</sup>

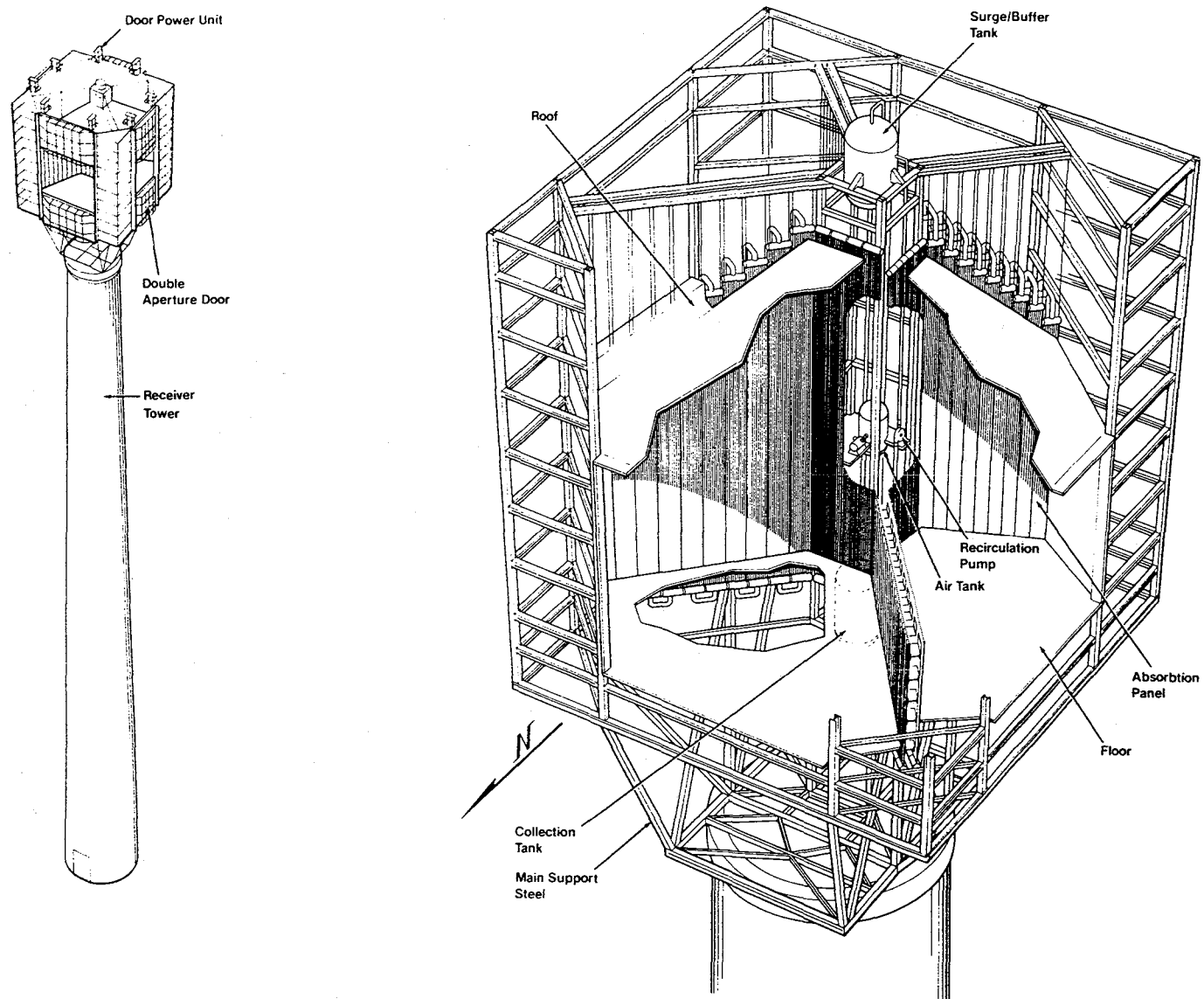


Figure 2-2. Babcock & Wilcox Quad Cavity Molten Salt Receiver Subsystem

four cavities along the back walls and along both sides of the common wing walls between cavities. The panels are heated from one side only. The latter feature is a major change from the earlier quad cavity repowering design, which had single wing walls heated from both sides. Detailed analysis of the single wing wall concept in this program revealed inadequate lateral support of the wing wall panels. The design change to double-sided wing walls was required to resolve the lateral support issue, but it entailed a large increase in receiver size, weight, and surface area and necessitated structural support. Parallel efforts to meet panel maximum temperature limits led to heliostat re-aiming strategies to achieve controlled changes in solar flux distribution on selected receiver panels.

The receiver configuration selected by Foster Wheeler uses a single, north-facing cavity with 20 modular absorber panels arranged vertically around the inside walls of the U-shape or "omega-shape" cavity. This study has dictated changes to the earlier Sierra Pacific repowering conceptual design in the shape of the cavity and in the size and arrangement of the receiver panels. A major design effort for the receiver doors (used to close off the cavity aperture) was also required, primarily because of the large size of the aperture in this single-cavity design.

For both designs, the salt flows in sequence through multiple, modular receiver panels composed of thin-walled metal tubes. Groups of panels are arranged into "control zones" which operate in parallel. The development of control strategies for operating these multiple zones in the presence of variable cloud cover was an integral, yet difficult part of the design efforts, complicated by the conflicting objectives of continuous delivery of full rated output and protection of the receiver panels from excessive heat due to overshooting the specified temperature.

Even with steady insolation levels, the restrictions on maximum permissible temperatures for metal and the requirements for adequate creep-fatigue lifetimes for the receiver panels dictated significant changes in the number, size, and arrangement of the panels for both receiver designs. Similar temperature and thermal stress factors (along with the required thin tube wall size) also presented a serious obstacle to joining absorber tubes to make a receiver panel assembly. The fabrication processes finally selected by each contractor were the result of extensive work in the areas of weld development and thermal stress analysis.

Both molten salt receiver studies have revealed important shortcomings in the repowering concepts upon which they were based. Changes to the initial concepts have resolved most (but not all) of the technical uncertainties identified during the contracted development efforts. Generally, the required changes have increased the size, complexity, and cost of the receiver subsystem. Final reports and cost figures will be published in FY 1983.

b. Sodium Receiver. The Energy Systems Group of Rockwell International funded the construction of a sodium-cooled test receiver for evaluation at the Central Receiver Test Facility (CRTF) in Albuquerque, New Mexico. The test program was funded jointly by the Energy Systems Group and DOE. The objectives of the program included providing a proof-of-principle

test of sodium-cooled receiver panels, gaining practical fabrication and operating experience, and establishing the capability to build commercial panels. The receiver, shown in Figure 2-3 mounted on the CRTF tower, consists of three 21-tube panels (19 mm outer diameter and 316 stainless steel tubing) operating in parallel, each panel having an independent control valve. Testing was conducted between October 30, 1981, and March 12, 1982, with a total test time of 75 hours. Major accomplishments included the following:

- (1) Operation in a solar flux density greater than  $1.5 \text{ MW/m}^2$
- (2) Operation at design temperatures [ $288^\circ\text{C}$  ( $550^\circ\text{F}$ ) inlet,  $593^\circ\text{C}$  ( $1100^\circ\text{F}$ ) outlet]
- (3) Maximum power level of 2.9 MWt at  $593^\circ\text{C}$  ( $1100^\circ\text{F}$ )
- (4) Demonstration of satisfactory receiver control
- (5) No major receiver subsystem problems

The test report will be published in FY 1983.

c. Air Receivers for Process Heat. Solar central receivers can potentially displace the fossil fuels used in many industrial process air systems. However, many different designs for air heating central receivers exist. To better direct the allocation of development funds within the Solar Central Receiver Program, a study comparing the cost and performance of central receiver process air systems was performed in FY 1982 to identify the relative cost-effectiveness of the systems.

This study considered seven air-heating receiver concepts. These concepts, listed in Table 2-2 with their respective proponents, exist in varying stages of development. Detailed preliminary designs have been prepared for some, while others are simply concepts. To assess the potential of each concept, Pacific Northwest Laboratory (PNL) was contracted to perform a cost and performance assessment of each receiver concept over a range of power levels, design temperatures, and operating pressures. The resulting conceptual designs, based on a uniform set of cost and performance assumptions, formed the basis for an evaluation of complete central receiver process air delivery systems.

The systems were optimized using the DELSOL2 computer code and were compared on the basis of the levelized cost of delivered energy in 1990. The evaluation revealed many disadvantages to the use of air as a heat transfer fluid. Heating a gas directly in a solar receiver is expensive because of the inherently poor heat transfer characteristics of gas. Thus, the receivers are large and often require expensive and exotic materials. The high cost of air receiver systems is primarily due to the large piping and compressor requirements and the energy needed to drive the compressor.

The study determined that the cost of delivered energy ranges from 17 to 28\$/MBtu (1982 dollars). It was concluded that the air receiver systems studied were not particularly attractive technological options for solar central receiver systems. The study recommended that alternative systems be pursued for high-temperature process air applications.



Figure 2-3. Sodium-Cooled Receiver Subsystem Research Experiment

Table 2-2. Receiver Concepts Analyzed by PNL to Develop a Common Basis for Receiver Cost and Performance Comparisons

Receiver Concept	Proponent	Level of Previous Analysis
Metal Tube	Boeing	Detailed Design Study
Ceramic Tube	Black and Veatch	Detailed Design Study
Sodium Heat Pipe	Foster Wheeler/Dynatherm	Detailed Design Study
Ceramic Matrix	Sanders	Model Testing/Preliminary Design Testing
Ceramic Dome	MIT Lincoln Laboratory	Model Testing
Small Particle	Lawrence Berkeley Laboratory	Model Testing
Volumetric	Pacific Northwest Laboratory	Preliminary Analysis

d. Convective Losses from Solar Central Receivers. The inability to predict the convective losses from a central receiver reduces the accuracy of cost and performance predictions of central receiver systems. In 1979, Sandia National Laboratories-Livermore (SNLL) established the Central Receiver Energy Loss Program to improve understanding and predictive capability in this area. The focus of this work has been the acquisition of experimental data under realistic and well-characterized conditions and the development of validated computer models. In FY 1982, two major experiments to measure heat transfer processes under conditions characteristic of external and cavity receivers were completed.

In one experiment, heat transfer from external receivers was examined through measurements on a large heated flat plate. This experiment was carried out via a joint program involving Nielsen Engineering and Research, Inc., and Stanford University. Local heat transfer and detailed measurements of the temperature and velocity profiles through the boundary layer were obtained. Measurements were made on the 3-by-3-m plate at temperatures up to 600°C (1112°F) and for air velocities from 0 to 6 m/sec.

In another experiment, natural convection heat transfer from a large heated cubic cavity was measured at SNLL. The walls of the 2.15-m cube were heated to temperatures from 90 to 750°C (194 to 1382°F). Measurements of temperature and velocity in the cavity aperture plane were used to estimate the convective losses.

These two experiments provided basic heat transfer data from large high-temperature surfaces in Grashof and Reynolds number regimes that previously had been unexamined. The data were used to obtain empirical correlations for

prediction of heat transfer coefficients. In addition, the cavity loss data were used to evaluate existing models of natural convection from cavity receivers. The external boundary layer data are being used at Stanford University in an ongoing program to develop a predictive computer code.

e. Solid Particle Receiver. An examination of the use of solid particles as the working fluid in a high-temperature solar central receiver system was initiated in FY 1982. A range of potential central receiver applications, including industrial process heat generation, fuels and chemicals production, and Brayton-cycle electricity generation, requires solar thermal energy production at temperatures above those which can be provided by the currently developed water/steam and molten salt technologies.

In FY 1982, a study identified potential limitations of high-temperature air receiver systems (e.g., their small volumetric heat capacity and large parasitic power requirements). In contrast to air, solid particles have a high volumetric heat capacity that is comparable to that of molten salt. In principle, solid particles may be moved within a central receiver system with solids lift equipment requiring minimal parasitic power.

The use of solids to absorb concentrated solar energy was investigated by several researchers at the Centre National de la Recherche Scientifique solar furnace in Odeillo, France. In the U.S., a preconceptual design using solid particles as the heat transfer and storage media in a central receiver was examined, and the results of the study were sufficiently promising to prompt a more detailed examination of the concept.

The U.S. study has focused on identifying the critical parameters that govern the technical feasibility of the concept for commercial-scale applications. Potential receiver designs were examined. A conceptual design of a free-fall receiver (Figure 2-4), in which sand-sized particles are heated by direct and reradiated solar insolation, has been proposed for further study. Material handling equipment and vendors have been identified. Eight candidate materials have been selected on the basis of potential material limitations such as particle fracture resulting from thermal shock and particle abrasion and sintering in the storage vessel. Models of radiative heating processes have been employed to predict the thermal performance of the receiver. In addition, the cost of energy delivered from a solid particle central receiver system has been estimated using the same methodology as the high-temperature air receiver study. This estimate, which indicates that the energy cost from solid particle receiver systems will be less than the energy cost from air systems, supports further work on the concept.

In FY 1983, a detailed investigation of performance of candidate particle materials will be undertaken and some testing initiated. Although these studies are required for more definitive conclusions, the work to date indicates that the use of solid thermal carriers in a solar central receiver is a promising technique for the generation of high-temperature solar energy for a variety of applications.

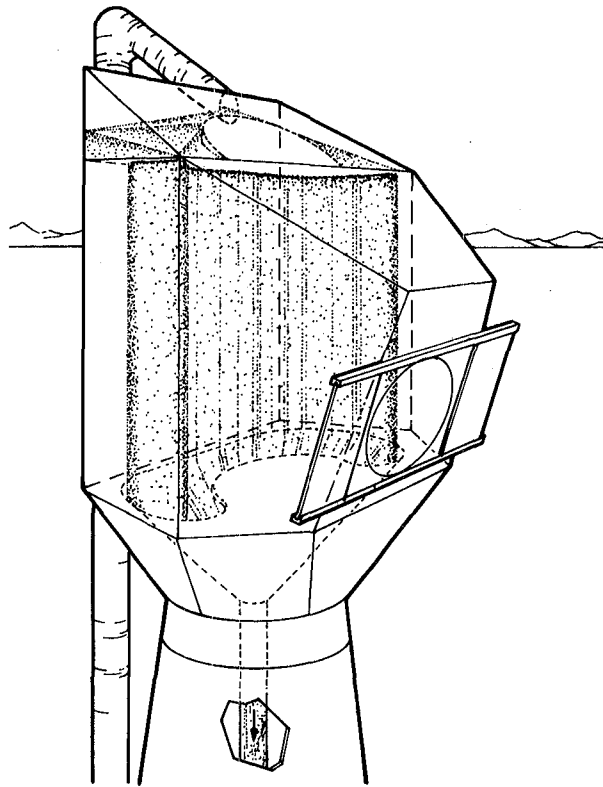


Figure 2-4. Schematic of Solid Particle Receiver

### 3. Steam Generator Development

If solar central receiver plants are to use molten salt for the receiver and thermal storage working fluids, molten salt steam generators must be developed. Two contracts were awarded in FY 1982 as the result of a competitive solicitation for the design, fabrication, and testing of molten salt steam generators for solar-electric power plant applications.

The steam generator concept selected by Babcock & Wilcox for both a 100-MWe stand-alone application and a 50-MWe repowering application is a forced recirculation system using horizontally oriented components (Figure 2-5). The preheater and evaporator are U-tube/straight-shell heat exchangers; the superheater and evaporator are U-tube/U-shell heat exchangers. The choice of horizontal orientation and forced circulation allows flexibility in arranging the components. In the stand-alone application, the components can be incorporated into a wing of the turbine building. For repowering applications, all components except the steam drum can be located at ground level on a single concrete slab foundation. This concept is an attractive one for potentially repowering utilities in the southwest. The U-tube heat exchanger design allows for differential thermal expansion between the tube bundle and the heat exchanger shell, and between individual tubes within the tube bundle. The U-shell design of the superheater and reheater separates the inlet and outlet tube sheets and eliminates the high thermal stresses that would occur in a single tube sheet.



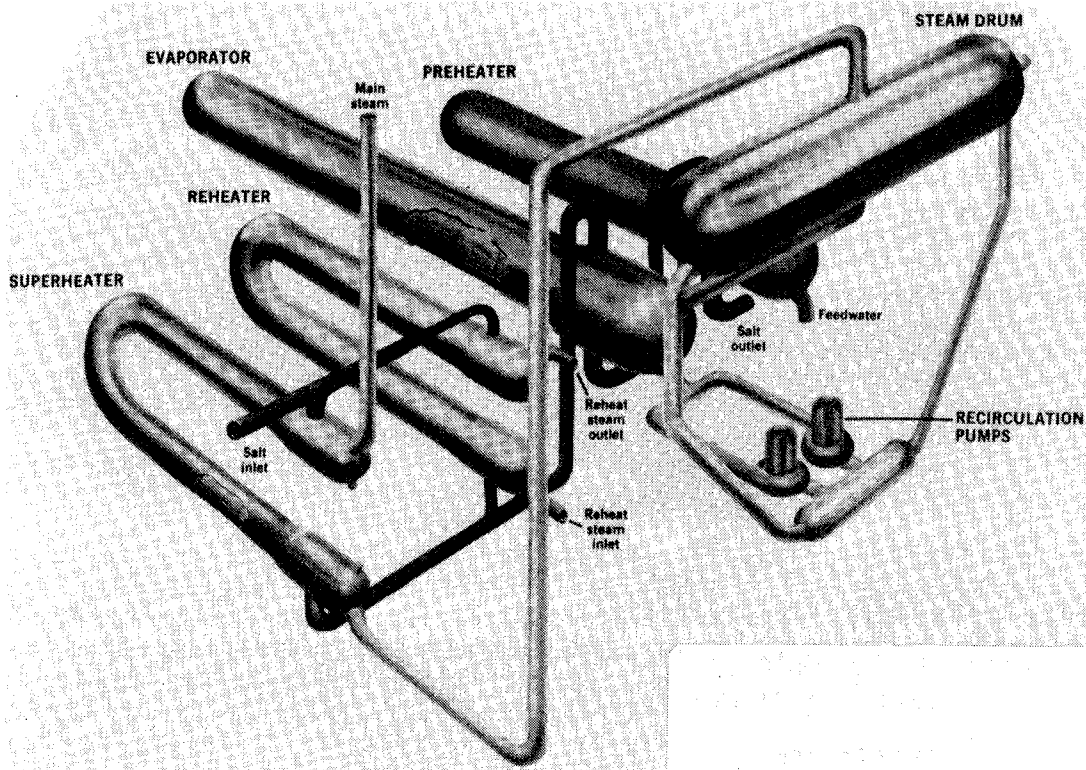


Figure 2-5. Babcock & Wilcox Molten Salt Steam Generator Subsystem

The baseline configuration selected by Foster Wheeler for both 100-MWe stand-alone and 50-MWe hybrid applications is a natural-circulation system that uses straight-tube/straight-shell components with expansion bellows for thermal expansion (Figure 2-6). All major components (preheater, evaporator with integral steam drum, superheater, and reheater) are in a vertical orientation. Heat transfer tube lengths are similar for all components of the 100-MWe design (17.5 to 18.9 m) and the 50-MWe design (16.8 to 18.6 m). Likewise, overall component heights are similar (except for the additional height of the integral steam drum on the evaporator). The major size difference between components and between the 100- and 50-MWe designs is the number of tubes required to achieve the heat transfer design requirement, which in turn affects component shell diameters. An additional difference is the location of the expansion bellows for the 100- and 50-MWe components: for the former, they are located on the water/steam inlet nozzle and for the latter, on the shell. Construction materials are carbon steel for the preheater and steam drum, 1.25 Cr/0.5 Mo steel for the evaporator, and 304 stainless steel for the superheater and reheater.

Major accomplishments in FY 1982 of the Phase I contracts included thermal/hydraulic design and basic sizing of components; structural analysis; definition of control and operating modes; development of a dynamic simulation model for analysis of subsystem and control response; definition of auxiliary equipment, structural support, and site installation requirements; and development of subsystem cost estimates and fabrication/erection plans. Foster Wheeler cost estimates for the 100-MWe design are \$15.2 million (installed

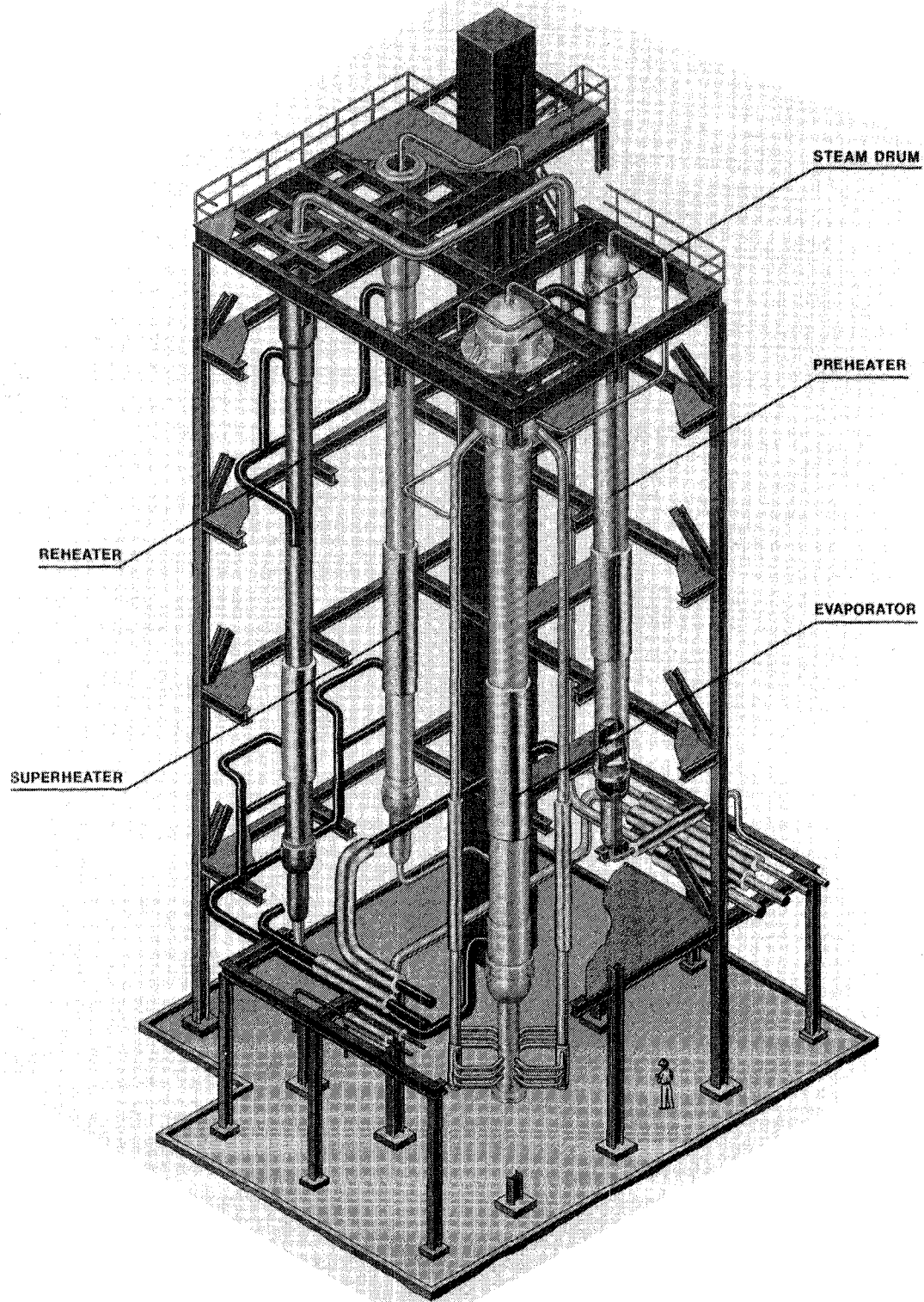


Figure 2-6. Foster Wheeler Molten Salt Steam Generator

capital cost, 1982 dollars) and \$11.3 million for the 50-MWe hybrid design. Babcock & Wilcox cost estimates for the installed steam generator subsystems are \$10.56 million (1982 dollars) for the 100-MWe stand-alone plant and \$7.61 million for the 50-MWe repowering application. These estimates include engineering, fabrication, controls, instrumentation, structure, auxiliaries, field construction, and construction management costs.

Proposals for a Phase II subsystem research experiment (SRE) were developed and presented as part of the Phase I contracts. Both Foster Wheeler and Babcock & Wilcox reported that there were no major materials, design, fabrication, or operational issues to be resolved in the SRE. The intent of the proposed SREs was to demonstrate complete subsystem operation. However, because of budget constraints and programmatic changes, a Phase II SRE was not funded. Certain applicable information gained during these contracts was applied to the salt steam generator for the Molten Salt Electric Experiment (Section II.B.4).

#### 4. Thermal Energy Storage

A molten salt thermal energy storage SRE was initiated in FY 1982 to analyze and experimentally resolve all important issues related to the design and development of a cost-effective subsystem for thermal energy storage (TES) using molten nitrate salt (60%  $\text{NaNO}_3$  - 40%  $\text{KNO}_3$  by weight) as the sensible heat storage medium. Participants included Martin Marietta Aerospace, American Technigaz, Inc., Arizona Public Service Company, and Stearns Roger. Key elements of the program include (1) preliminary design and cost analysis of a 1200-MWt-h commercial-size TES subsystem, (2) a development program for critical components of the subsystem design, and (3) design, construction, and testing at the Central Receiver Test Facility of a small-scale (7-MWt-h) SRE.

The baseline design for the TES subsystem (Figure 2-7) uses separate cylindrical hot (565°C, 1049°F) and cold (288°C, 550°F) tanks. The cold tank has an internal carbon steel structural shell with external insulation. The hot tank has an external carbon steel structural shell, internal insulation of firebrick, and an internal insulation liner made of a "waffled" Incoloy 800 membrane. An internal liner was necessary to prevent the molten salt from contacting the refractory insulation because of material incompatibilities at operating temperatures. The "waffle" configuration accommodates the thermal expansion and contraction of the membrane liner. Both hot and cold tanks are placed on insulated cast foundations, which are water-cooled to prevent excessive heating of the supporting soil.

Testing was accomplished between January and April 1982. As a result of design studies and the SRE, the technical feasibility of the baseline TES configuration has been established. The estimated cost is 10.8\$/kWt-h for a 1200-MWt-h storage system. Some problems were experienced in the SRE with control valve performance, drying out of the castable insulation supporting the tanks, and higher-than-expected thermal losses from the cold tank. Martin Marietta believes the latter may be due to degraded tank insulation, which could have resulted from water being driven out of the castable foundation during curing. The performance implications of small, undetected leaks in the hot tank liner and the need for a better method of calculating long-term creep-fatigue lifetimes for the liner have been considered.

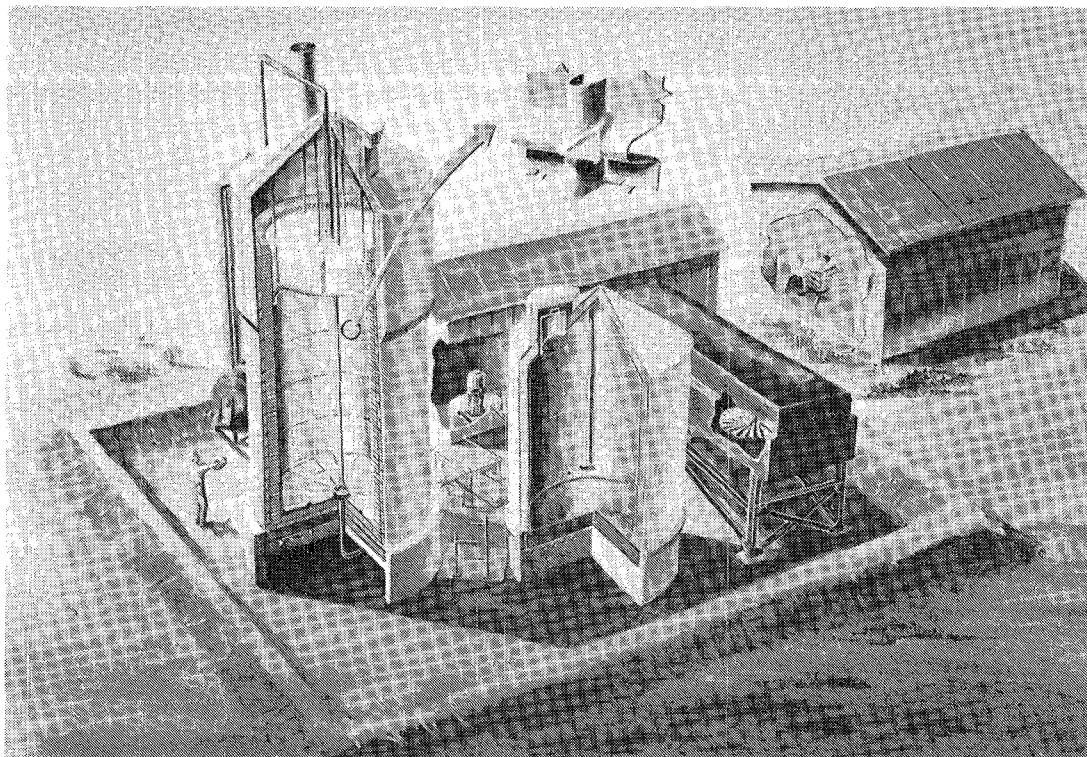


Figure 2-7. Molten Salt Storage SRE

## B. SYSTEMS EXPERIMENTS AND ANALYSES

### 1. 10-MWe Central Receiver Pilot Plant

The 10-MWe Central Receiver Pilot Plant (Solar One) near Barstow, California, is the world's largest solar-electric generating station (Figure 2-8). This pilot-scale research and development experiment is a cooperative effort between government and private industry to demonstrate technical feasibility, economic potential, and environmental acceptability of the solar thermal central receiver concept. The plant is located in the Mojave Desert on 526,110 m<sup>2</sup> (130 acres) of Southern California Edison Company's Cool Water Generating Station near Barstow, California. It is designed to produce at least 10 MW of electrical power to the utility grid (after supplying the plant parasitic power requirement) for 7.8 hours on the plant "best design day" (summer solstice) and for 4 hours on the plant "worst design day" (winter solstice). Solar One is a joint project of the Department of Energy (DOE), Southern California Edison (SCE), the Los Angeles Department of Water and Power (LADWP), and the California Energy Commission. The solar portion of the facility was designed and constructed by DOE, and the turbine/generator facilities (including the control building) were designed and constructed by SCE.

The central receiver concept being demonstrated at the Barstow plant integrates operation of six major systems (Figure 2-9). The collector system, consisting of large sun-tracking mirrors (heliostats), concentrates the solar energy on a tower-mounted receiver (boiler). There the solar energy transforms



Figure 2-8. 10-MWe Central Receiver Pilot Plant near Barstow, California

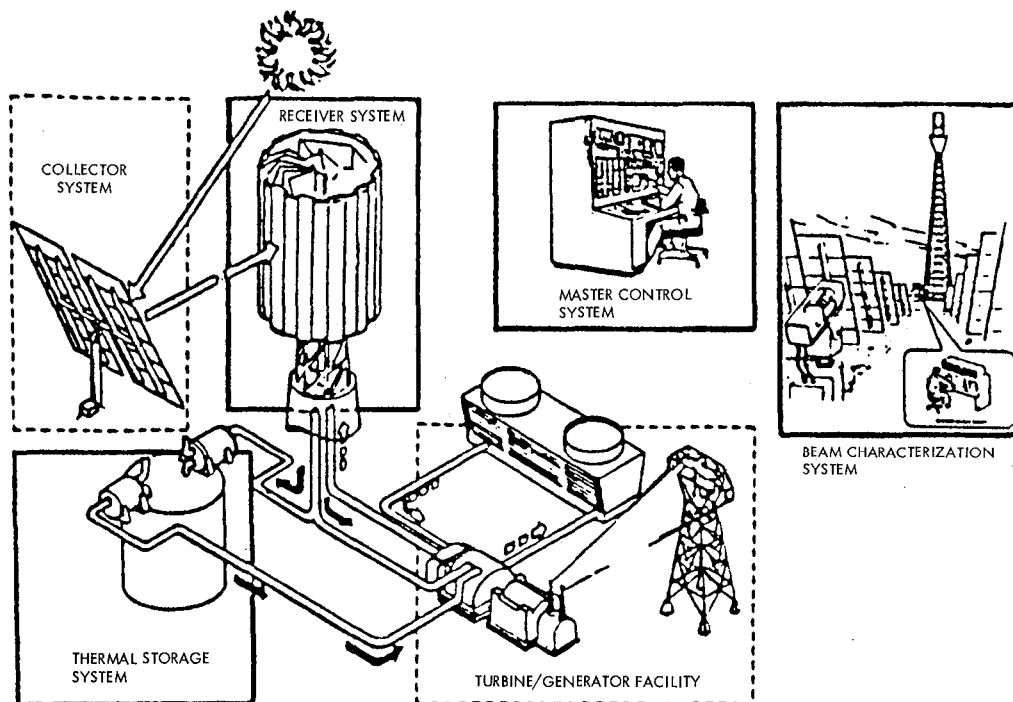


Figure 2-9. Six Major Systems of the 10-MWe Pilot Plant

water into superheated steam, which is used to drive a turbine/generator or is diverted to charge the thermal storage system. The thermal storage system stores the energy as sensible heat, which can be used to extend turbine/generator operation after sunset. The electric power generation system (turbine/generator) can generate 10 MW from receiver steam and 7 MW from thermal storage steam. The master control system is a series of computers that monitors and controls each of the major systems. The beam characterization system is used to align the heliostats and ensure their efficient operation.

a. Collector System. The collector system is a 360-degree array of 1818 Martin Marietta sun-tracking heliostats of the type shown in Figure 2-10. The heliostat field has a reflective area of 72,600 m<sup>2</sup> (782,000 ft<sup>2</sup>). Each heliostat is made of 12 slightly concave mirror panels totaling 39.9 m<sup>2</sup> (430 ft<sup>2</sup>) of mirror surface. The mirror assembly is mounted on a geared drive unit for azimuth and elevation control.

The collector control system consists of individual microprocessor heliostat controllers, 64 heliostat field controllers for control of groups of up to 32 heliostats, and double-redundant central computers called heliostat array controllers (HACs). Information on the annual and daily sun position required for aiming each heliostat is stored within this control system. The heliostats can be controlled individually or in groups in either manual or automatic modes through the HAC, which is located in the plant control room.

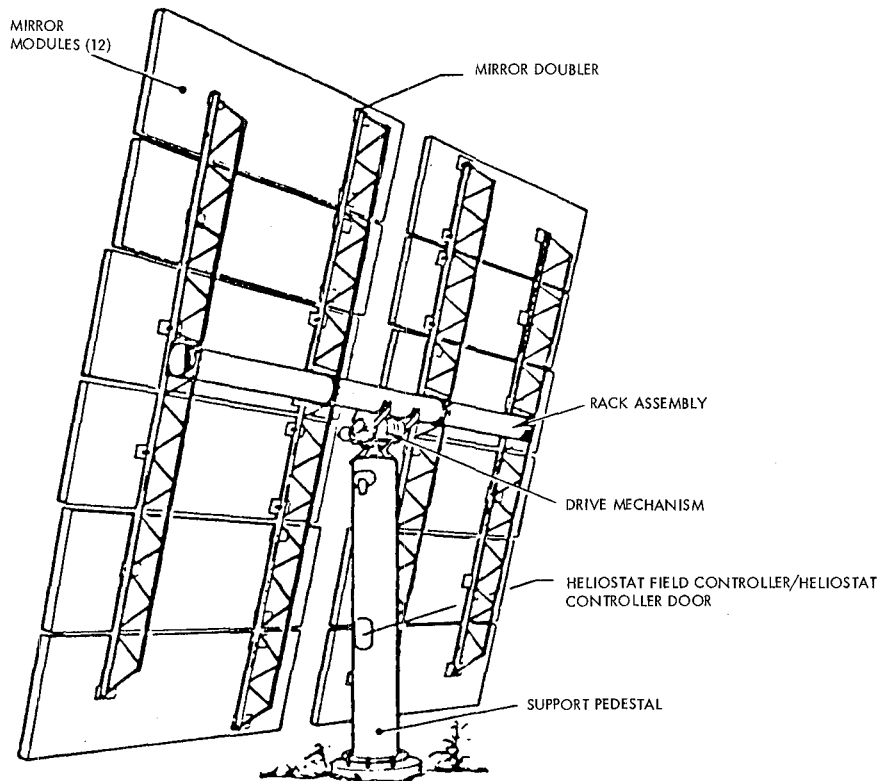


Figure 2-10. Martin Marietta Heliostat



The heliostats are designed to operate in winds up to 22 m/sec (50 mi/h) and will withstand winds up to 40 m/sec (90 mi/h) when stowed in a mirror-facedown position.

During a routine inspection about 7 months after installation, several mirrors in the heliostat field showed signs of silver deterioration (manifested as black spots on the mirror). As a result, studies were undertaken to analyze the corrosion. The results of these studies are summarized below:

- (1) Mirror corrosion is caused by water contact on the mirror backing.
- (2) The water found in the modules entered through the edge seal.
- (3) The field reflectivity loss as a result of corrosion was much less than 0.01%, with noticeably corroded areas on about 2% of the modules.
- (4) Methods were studied to remove existing trapped water and prevent future infiltration in the pilot plant modules.

Investigation and analysis of the mirror corrosion problem will continue in FY 1983.

b. Receiver System. The receiver system consists of a single-pass-to-superheat boiler with external tubing, a tower, pumps, piping, wiring, and controls necessary to provide the required amount of steam to the turbine. The receiver is designed to produce 510°C (950°F) steam at 10.1 MPa (1465 psia) at a flow rate of 14.1 kg/sec (112,000 lb/h). The receiver has 24 panels (6 preheat and 18 superheat), each approximately 0.91 m (3 ft) wide and 13.7 m (45 ft) long, as shown in Figure 2-11.

Physical construction of the plant was completed in the fall of 1981, and early 1982 activities centered on checkout and activation of the plant support systems. Cold flow testing was conducted on the receiver to ensure that all valving and piping were functional. Before receiver steaming operations could be initiated, however, curing of the absorptive paint on all 24 receiver panels was required. Solar radiation was needed for this procedure, and, for the first time, several of the major systems of the plant were operated together. Delays were encountered, however, because in February 1982 periods of sustained insolation were rare. Insolation for the entire year of 1982 was below normal, possibly because of particulates in the atmosphere from volcanic activity at El Chichón, Mexico.

Under the supervision of DOE and SNLL, weekend power production was performed for four successive weekends before the plant was released for limited power production. The operators were required to monitor parameters of receiver performance, which would have been monitored automatically had performance testing been completed. The full data acquisition system capabilities of the plant were deemed necessary for operation. This function, normally not associated with plant operation, was accepted by the operators

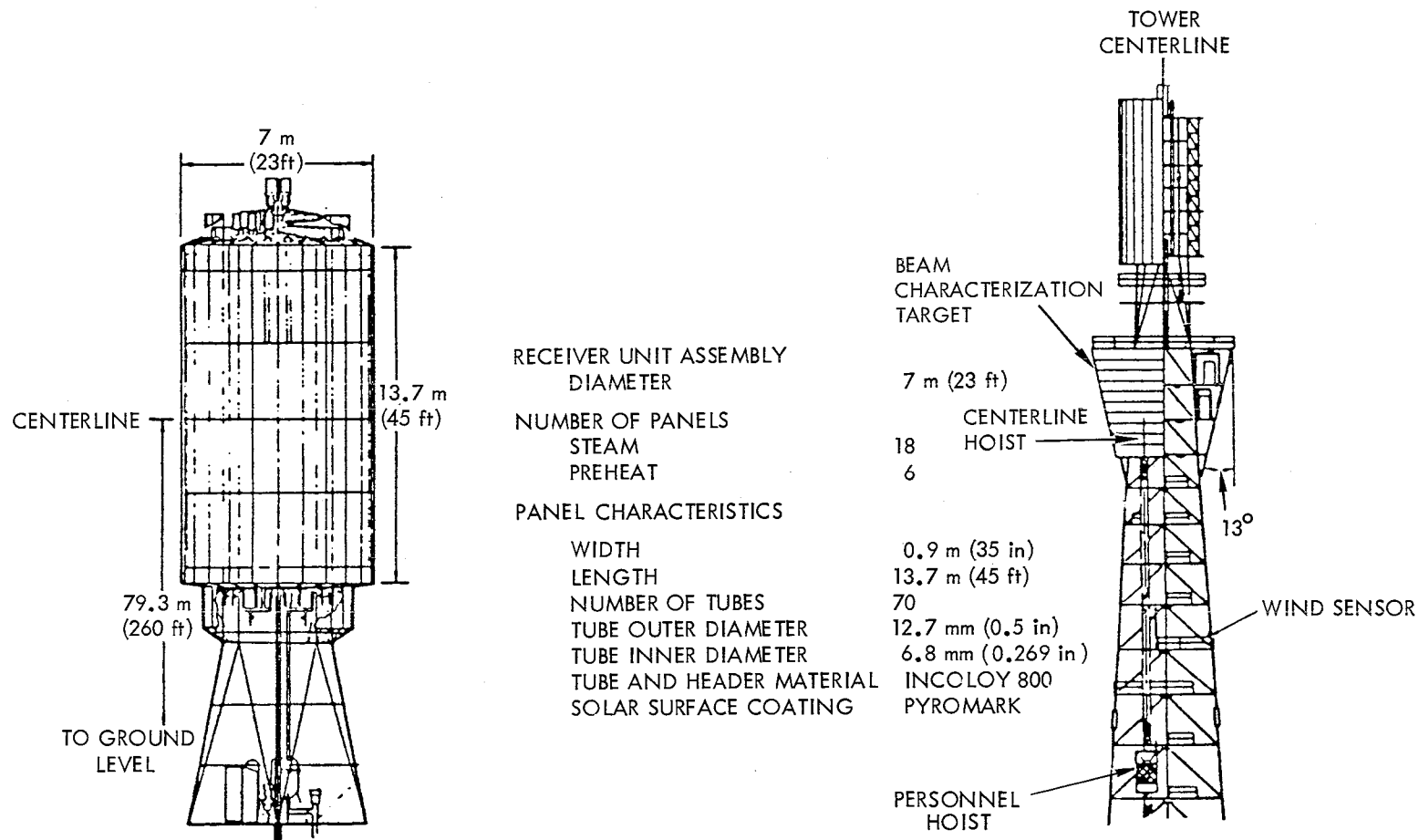


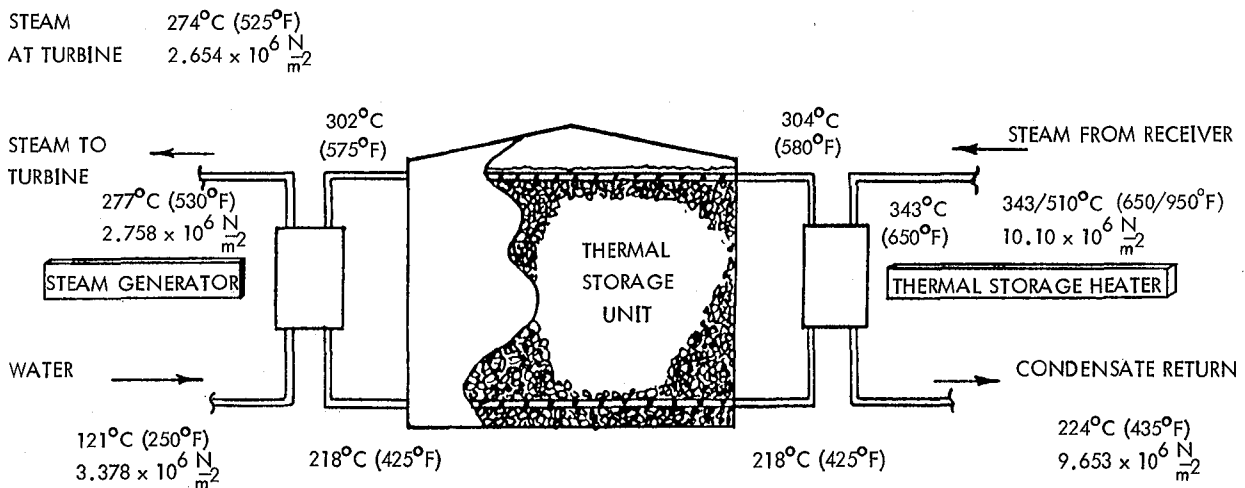
Figure 2-11. 10-MWe Pilot Plant Receiver System



without difficulty. Availability of the data system, which was originally provided to furnish engineering information, was a key factor in achieving early power production. The projected schedule for performance testing was met.

c. Thermal Storage System. By storing solar energy, the thermal storage system provides the capability to extend the power plant's operation into nighttime hours and periods of cloud cover and to supplement steam production when insolation is low. It also provides steam for maintaining selected portions of the plant in a warm status during nonoperating hours and for plant start-up the following day. The thermal storage system is shown schematically in Figure 2-12.

An oil leak in the thermal storage tank was discovered in August 1981 and repaired in February 1982 by welding a metal patch over the leak. The leak was caused by a manufacturing defect (a bubble or inclusion) in a 0.95-cm-thick plate that is part of the tank bottom. To locate and obtain access to the leak, a 1-by-1.3-m tunnel approximately 2 m deep was excavated into the insulating concrete below the tank; the tank bottom was supported by 15-ton jacks during the excavation. After the leak was repaired, the jacks were left in place and the excavation was back filled with insulating concrete. Extensive thermal stress analysis was performed to verify the soundness of the repair method because the tank is filled with thermal storage media consisting of 6.4 million kg of rock/sand and 0.91 million liters of heat transfer oil.



NOTES:

DISCHARGE TIME, 4 h  
EXTRACTABLE CAPACITY, 145 MWt-h  
CHARGING RATE, 1.6 to 31.6 MWt  
DISCHARGING RATE, 1.7 to 33.3 MWt

Figure 2-12. 10-MWe Pilot Plant Thermal Storage System

All functional checkout of piping, control valves, and control systems was delayed until repair of the tank leak. To make up the six-month delay, a rental boiler was brought to the site in April 1982. This unit was used to preheat the oil/rock/sand medium to 150°C (302°F) to evaporate water and volatile hydrocarbon fractions. In addition, oil flow was started in the charging and discharging heat exchanger trains, and water was circulated through the discharge heat exchanger trains to start the piping cleanup process. Ultimately, the thermal storage system was available to accept receiver supplied steam at the approximate time the receiver was capable of supplying it.

d. Master Control System. The master control system (MCS) is a series of computers that controls the plant from the central control room. This system supplies overall coordinated supervisory control to individual systems. A sketch of the master control console is shown in Figure 2-13. Ultimately, plant operation will be fully automatic with an operator override option. Initially, however, the plant systems must be operated separately by multiple operators.

To augment the master control system and to provide individual system control and trouble isolation, each system has its own distributed process controller. The process controllers, which are digital computers tied into the master system, control the system valves, motors, pumps, relays, and other

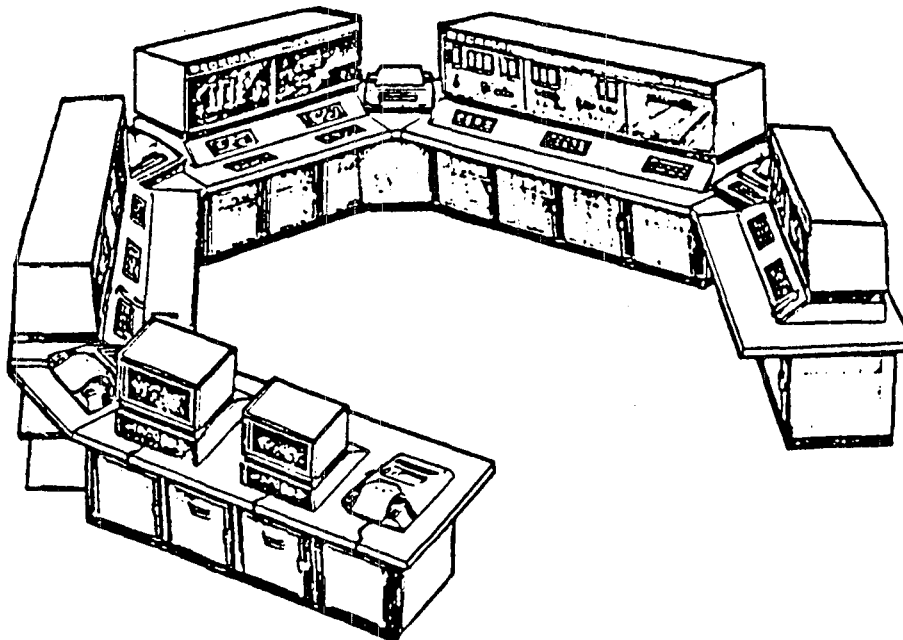


Figure 2-13. Drawing of Master Control Console at the 10-MWe Pilot Plant

equipment. They are located near the respective system's hardware in remote stations. For example, the process controller for the receiver is located in the tower within a remote station immediately beneath the receiver. Because of construction funding limitations, design and implementation of the supervisory operating control system element of the MCS is being deferred until FY 1983 and 84.

e. Turbine/Generator System. The General Electric turbine/generator is rated at 12.5 MWe and is a single case design for cyclic duty. It is a general type of machine also used for industrial and marine drives. The turbine has two steam admission ports: one high-pressure port for receiver steam and a lower pressure port for thermal storage steam because the storage medium is limited to 315°C (600°F). The rated turbine thermal-to-electric efficiency from receiver steam is 35% and from thermal storage steam 25%.

As a safety measure, receiver steam can be quickly routed to the condenser by an 8-in. modulating valve. This valve, which has high performance requirements, failed in early July. The cause was extreme thermal cycling conditions: Valve internals were subjected to transients that raised the temperature from ambient temperature to as high as 370°C (700°F) in seconds during start-up. Replacement of the valve internals was accomplished, the valve body was instrumented to record thermal history, and daily start-up of the receiver was delayed by approximately 1 hour to allow the valve body to warm up. Subsequently, the valve was electrically trace heated as a field modification, and, with preheating before dawn, the warm-up time has been reduced to approximately 5 minutes. The manufacturer believes that the valve internals will perform satisfactorily for at least 2 years under these conditions.

f. Beam Characterization System. Because each mirror module (glass facet) can be canted in two axes, the overall beam from each heliostat can be focused. The beam characterization system (Figure 2-14) is used to calibrate each individual heliostat beam with respect to its aim point on the receiver, its beam shape, and the beam power density. This system consists of a vidicon camera, a microcomputer, and associated controls and is coupled to the collector control system. The flared area of the tower immediately beneath the receiver is formed by four white painted aluminum sheet-metal targets, which are used for the beam characterization system. Some of the system's planned automatic and analytical capabilities have been deferred until FY 1983 because of construction funding limitations. Problems were experienced in operating the system in the automatic mode; efforts to solve these problems were ongoing at the end of the fiscal year.

g. Operational Summary. Three activities being performed concurrently during the two-year test and evaluation phase are (1) checkout of all plant operating modes, (2) upgrading of displays and incorporation of automatic control, and (3) testing and evaluation of performance. Early in the year, testing was hampered by long periods of cloud cover (Figure 2-15). Table 2-3 summarizes plant activities from April through September 1982. In conjunction with testing, electrical power was generated as shown in Figure 2-16. Plant availability is shown in Figure 2-17.

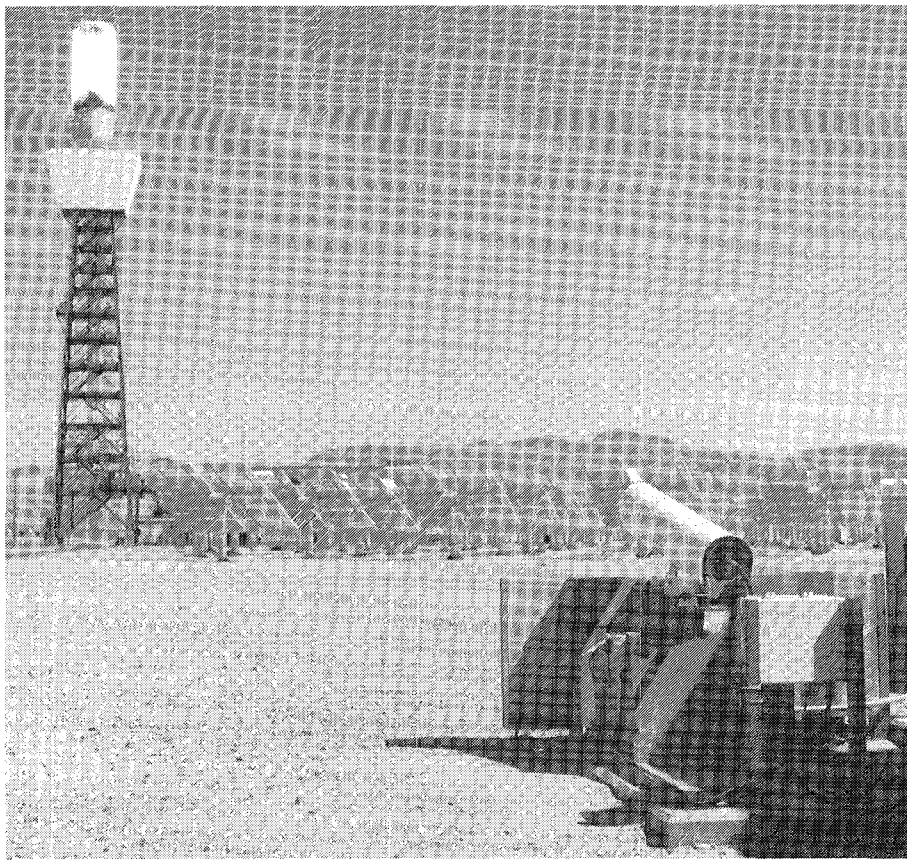


Figure 2-14. Solar One Beam Characterization System

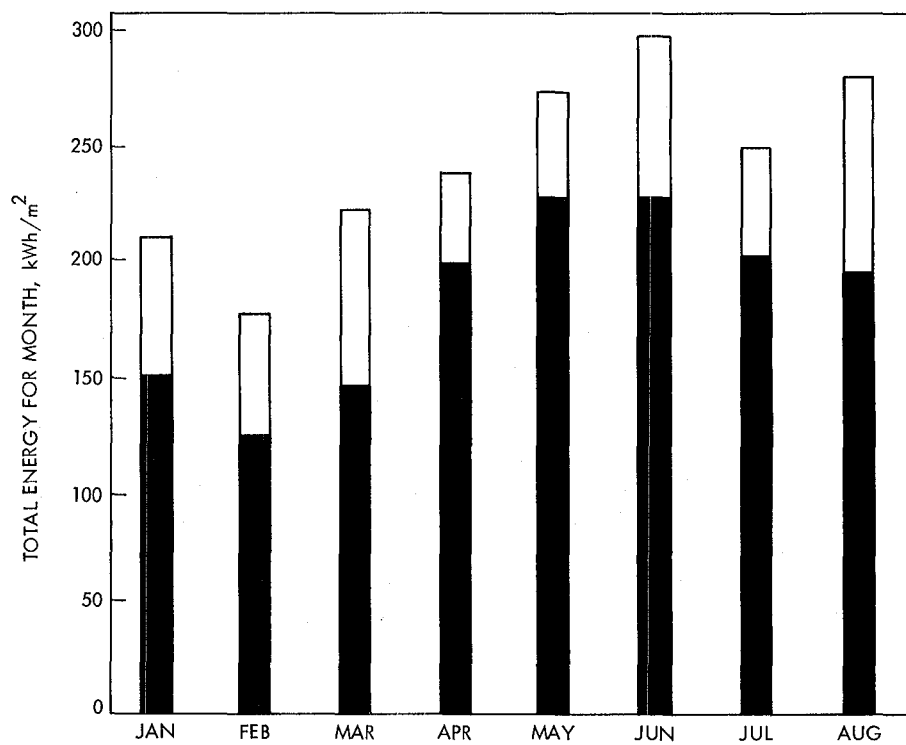


Figure 2-15. Direct Normal Insolation for 1982 (Shaded) and 1976 at Barstow, California

Table 2-3. FY 1982 Monthly Activity Summary for Solar One

	April	May	June	July	August	Sept
	hours					
Test	62	46.5	41	93	94	124
Plant Outage	61	59	88	96.5	73	75
Weather Outage	7	34	31	50	102	120
Power Production	28	48	10	29	27	55
MWe-h net	56.4	215.3	46.7	98.5	142.5	109.1
Total MWe-h net	56.4	271.7	318.4	416.9	559.4	668.5
<u>Activities</u>						
Receiver Control Test	██					
Storage Activation	████████████████					
Storage Testing	██					
Receiver/Turbine Testing	████████					
Weekend Power Production	██					

## 2. Small Solar Power Systems Project

The Small Solar Power Systems (SSPS) Project to design and build a two-system solar thermal power plant near Almeria, Spain, was begun in 1977 by members of the International Energy Agency (IEA). Nine IEA member countries are cooperating in the effort: Austria, Belgium, Germany, Greece, Italy, Spain, Sweden, Switzerland, and the United States. The systems, a central receiver system and a distributed collector system (described in Section IV.B.3), are based on technology available at the time of design with a minimum of research and development effort. The SSPS plant was completed and put into operation by the end of FY 1981; the test and operations phase has begun and will proceed through the end of 1983. An aerial view of the two-system SSPS Project is shown in Figure 2-18.

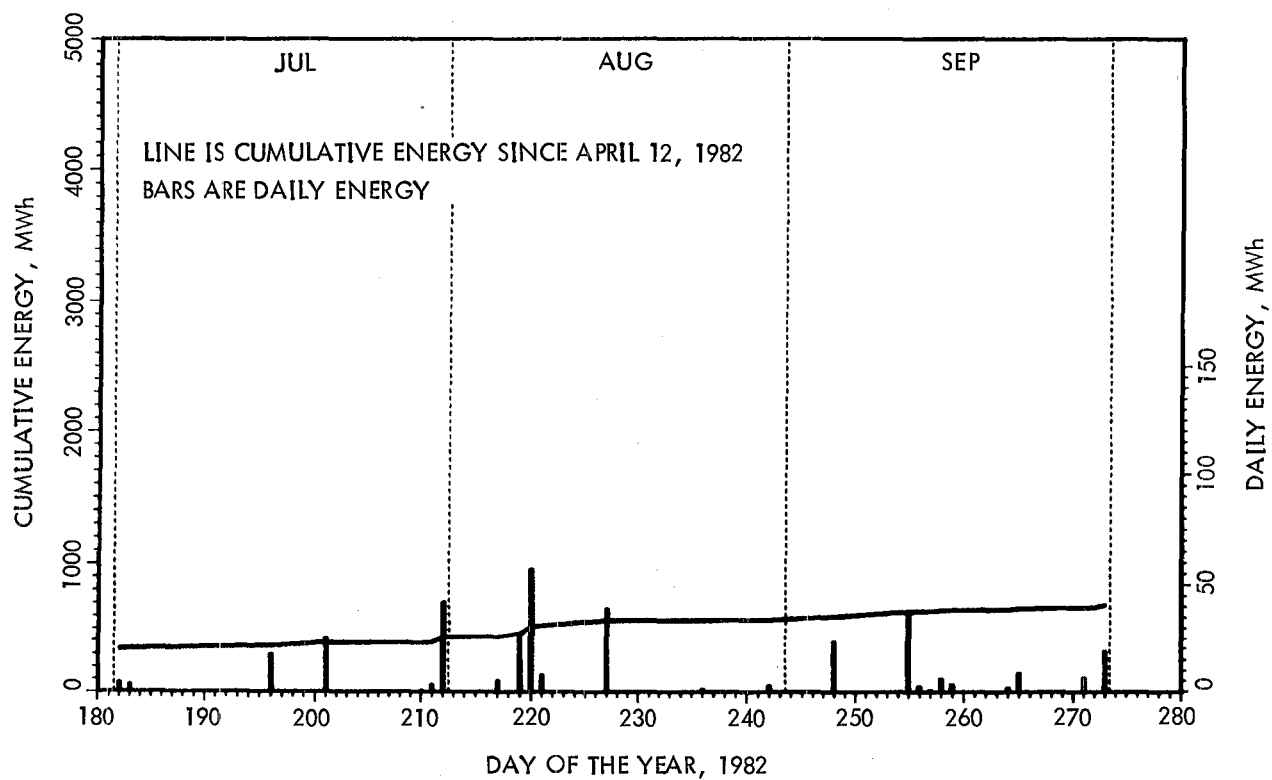
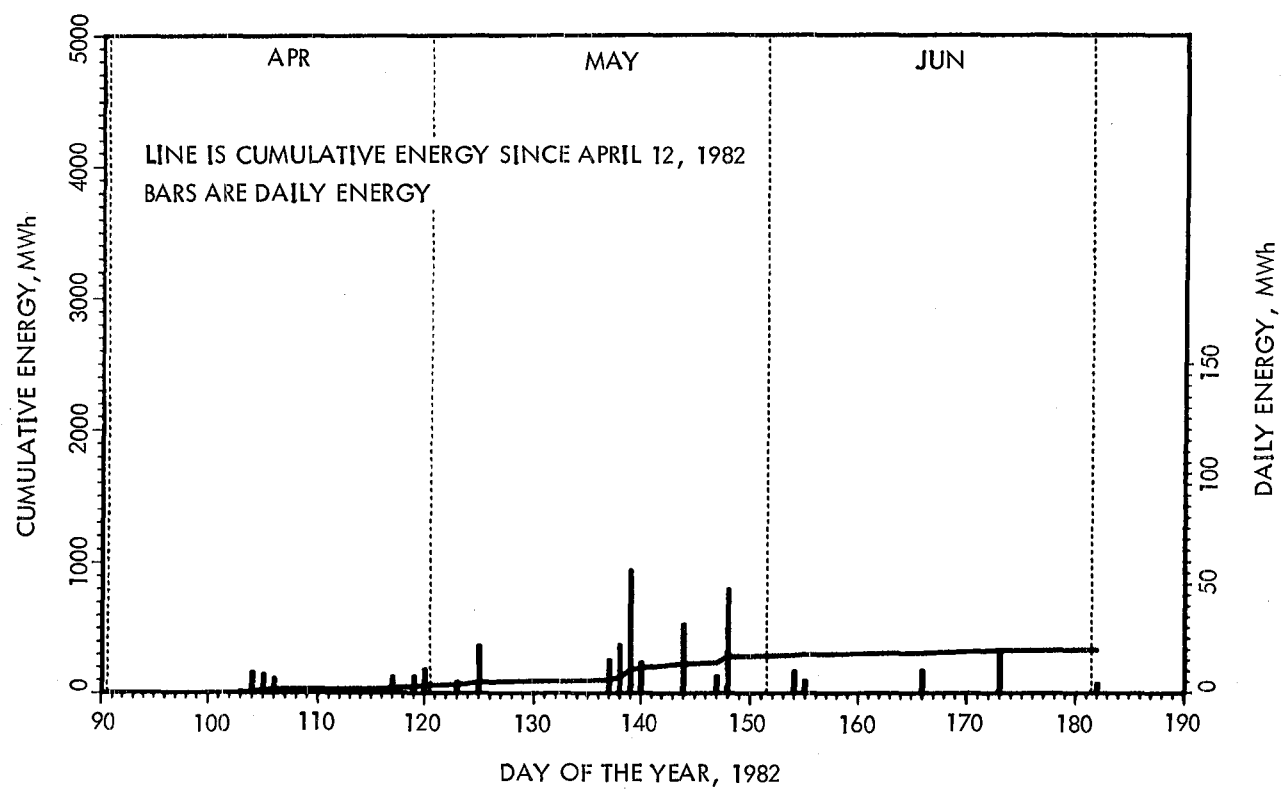


Figure 2-16. Solar One Net Electrical Production

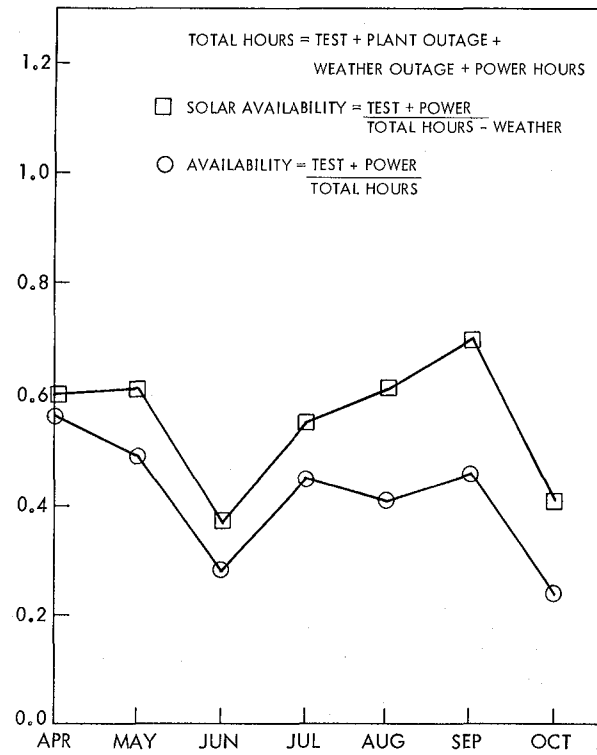


Figure 2-17. Solar One Plant Availability



Figure 2-18. Aerial View of the SSPS Project in Almeria, Spain

The SSPS central receiver system uses liquid sodium as the primary heat transport fluid in the receiver as well as for the storage system. Liquid sodium is one of the heat transport fluids currently being evaluated by the U.S. Solar Thermal Central Receiver Program. Because there are no sodium central receiver power plants under construction in the U.S., this project will provide the central receiver program with necessary plant operations and maintenance data.

The three major systems of the 500-kWe central receiver system plant are the heliostat field, the sodium heat transfer system, and the power conversion system. The south-facing heliostats direct reflected solar energy to a tower-mounted cavity-type receiver. Thermal energy from the receiver is piped to a hot storage tank and then to a steam generator for the production of superheated steam, which in turn is fed to a steam motor to produce mechanical energy to drive an electric generator.

a. Central Receiver System Heliostat Field. The 93 heliostats in the central receiver system field are the Martin Marietta type used for the central receiver pilot plant near Barstow, California. During FY 1982, the heliostat field was operated almost every day to gain operating experience. When the balance of the plant was not operational, the heliostat field was operated at standby, tracking a point near the receiver; otherwise, it tracked the receiver. In April 1982, a lightning strike occurred near the site, hitting a power line connected to the facility. Because the lightning protection for the site transformer on that power line had not been installed, a high-voltage pulse appears to have been on the collector field power line. Communication was lost with the entire heliostat field. After the receiver and transmitter in the heliostat field controller/heliostat array controller interference box were replaced, communication with the field was reestablished. However, after this repair work, 30 heliostats did not respond to commands. When damaged heliostat field controllers and heliostat controllers were replaced, all heliostats became operational.

b. Central Receiver System Receiver and Storage. The Interatom-designed north-facing cavity receiver, which uses sodium as the heat transfer fluid, has worked as designed when the balance of the plant has been operational. The thermal storage system consists of two vessels, one for cold storage to supply the receiver and one for hot storage to store sodium from the receiver. In May and July 1982, the sodium pump that supplies sodium from the hot storage vessel to the steam generator failed because of oil leaks in the pump motor. Each time failures occurred, repairs were made to the pump. Leaks that had occurred in the cold storage vessel in July 1981 reoccurred in September and October 1982. Repairs were made after the September leak, but when the vessel leaked again in October, the plant was shut down. (Since that time, it has been decided to remove the portion of the cold vessel that is leaking and replace it with a new section.) The sodium inlet system is being redesigned to alleviate the leakage problem, believed to be the result of inadequate design and unsatisfactory workmanship.



c. Central Receiver System Steam Generator and Power Conversion Unit. The steam generator is a helical-tube once-through type in which sodium from the hot sodium storage vessel is used to produce superheated steam. Sodium from the steam generator is returned to the cold storage vessel. A steam motor is used as the power conversion system. The steam generator has operated when possible without problems. However, the steam motor, which first failed in September 1981, has only operated intermittently during FY 1982. After each failure was repaired, a different failure would occur. These problems are believed, in part, to be the result of condensation (water) seeping into the cylinders of the steam motor. It has been decided to redesign the steam piping system to include condensate drains at all critical locations and thus prevent condensate from entering the steam motor.

d. Test and Operations. During FY 1982, continuous operation of the central receiver system has been minimal due to problems with hardware and poor weather. With much time and effort being expended to ready the plant for operation, little performance evaluation has been conducted.

### 3. Repowering System Designs

a. Conceptual Designs. Five repowering advanced conceptual design contracts were completed in FY 1982. The goals of this phase of the repowering program were to (1) allow the most recent developments in central receiver technology to be incorporated into the designs, (2) ensure that system performance specifications are based on performance characteristics of commercially available components, and (3) conduct trade-off studies to optimize the collector field size, receiver output power, energy storage capacity, electrical-to-thermal output ratio (cogeneration only), and solar energy dispatch strategy. Major participants in the conceptual design study are shown in Table 2-4.

The five design studies were completed by June 30, 1982. During the studies, each contractor team refined and updated its design and made major changes to improve the economics of these first-of-a-kind plants. Power levels were reduced to lower capital costs for the Arizona Public Service and Sierra Pacific Power designs, and, to a lesser extent, the El Paso Electric design. The plant economics did not improve, but with system sizes still adequate for initial plants, a much lower initial investment resulted from the changes.

Capital costs for these first plants is high, principally due to the cost of the heliostats. With current high interest rates, these plants are not economical using conventional financing; however, third-party financing with present tax credits and short depreciation periods would provide an acceptable rate-of-return if energy could be sold for the price of power from displaced oil.

b. Preliminary Designs. As the last stage preceding final detailed design and construction, four repowering preliminary design contracts were awarded in September 1982 on a cost-shared basis. The overall objective

Table 2-4. Systems Summary of Advanced Conceptual Designs for Repowering

	El Paso Electric	Rockwell	McDonnell Douglas	Bechtel	Arizona Public Service
Receiver	External Cylindrical Evap/Reheater Water/Steam	External Cylindrical Sodium	Partial Cavity Salt	Twin Cavity Water/Steam	Quad Cavity Salt
Receiver Power, gross	41 MWe	60 MWe	35 MWe	31.8 MWt	66 MWe
Heliostat:					
Field	160° North	Surrounding	130° North	150° North	Surrounding
Type	Generic 2nd Generation	MDAC 2nd Generation	MDAC 2nd Generation	ARCO 2nd Generation	MMC 2nd Generation
Number	2998	6776	2565	1020	5000
Area, m <sup>2</sup>	57	57	57	53	57
Cost, 1982 \$/m <sup>2</sup>	251	219	240	410	263
Storage:	None	Air/Rock	Hot/Cold Salt Tanks	Bagasse	Hot/Cold Salt Tanks
Capacity	-	4 h/580 MWt-h	3 h/278 MWt-h	880 tons	4 h/688 MWt-h
System Net Elec. Eff. Annual Average, %	15	20	24	17	20
Annual Energy-Thermal, GWh	213	474	234	68	416
Project Cost, 1982 \$M	89	148	99	45	132
Annual Oper. & Main., % project cost	0.6	0.4-1.2	0.5	1.1	1.1

of this phase is to develop, using state-of-the-art central receiver technology, site-specific preliminary designs for repowering facilities having the potential to be economically competitive with fossil-fueled plants. The conceptual designs selected have the greatest chance for construction in the next five years in the absence of further government funding. Table 2.5 lists the participating contractor teams and provides key features of each design.

As shown in Table 2-5, of the teams that participated in the Advanced Conceptual Design phase, three elected to employ third-generation,  $95\text{-m}^2$  heliostats as their baseline design. Other significant changes include:

- (1) Arizona Public Service changed their concept from a quad-cavity receiver with a surrounding heliostat field to a partial cavity utilizing a north field.
- (2) ESG (Energy Systems Group, Rockwell) changed their 60-MWe cylindrical receiver design to a 30-MWe, north-facing, flat-plate receiver design. The storage system was changed from 4 hours of air/rock storage to 70 minutes of sodium storage in separate hot/cold tanks.

Completion of the preliminary design contracts is scheduled for September 1983.

#### 4. Molten Salt Electric Experiment

A complete molten salt system experiment (Figure 2-19) is being built that will integrate the major components of a molten salt system. Two of these three components, the receiver and the thermal storage unit, have already been built and tested as subsystem research experiments (SREs). The third component, a molten salt steam generator, is being built for the full system experiment. The tower and heliostat field at the CRTF are already available to concentrate solar energy on the receiver. A turbine/generator of appropriate size and steam requirements is being purchased. The objectives of this project are to:

- (1) Verify the technical feasibility of a molten salt central receiver system
- (2) Develop automatic controls for a central receiver system
- (3) Familiarize utilities with molten salt system operations and maintenance
- (4) Gain operating experience with existing hardware including the molten salt receiver and storage SRE hardware at the CRTF

The experiment will be constructed and operated by a consortium of utilities and industry. This consortium will also supply approximately half of the funding. DOE, through SNLA, will supply on-site labor and facility hardware at the CRTF.

Table 2-5. Repowering Preliminary Designs

Prime and Subcontractors	Facility	Application	Receiver Type	Storage	Collectors
Amfac Energy Arco Bechtel	Pioneer Sugar Mill, Maui, Hawaii	Cogeneration, 32 MWt	Twin cavity, water/steam	Biomass (bagasse)	600, 95 m <sup>2</sup> Arco 3rd-generation heliostats, north field
Arizona Public Service Babcock & Wilcox Black & Veatch Martin Marietta (MMC)	Saguaro Plant, Phoenix, Arizona	Repowering, 60 MWe power production	Single cavity, molten salt	4 hours at rated output	4850, 58.5 m <sup>2</sup> MMC 2nd-generation heliostats, north field
El Paso Electric Babcock & Wilcox Stone & Webster Westinghouse	Newman Station, El Paso, Texas	Repowering, 41 MWe power production	Exposed, half-cylinder, water steam	None	1878, 95 m <sup>2</sup> generic 3rd-generation heliostats, north field
ESG (Rockwell) PG&E (Pacific Gas & Electric) Arco	New Facility, Carrisa Plains, California	Provide 30 MWe to PG&E grid	Flat plate, liquid sodium	70 minutes at rated output	1877, 95 m <sup>2</sup> Arco 3rd-generation heliostats, north field

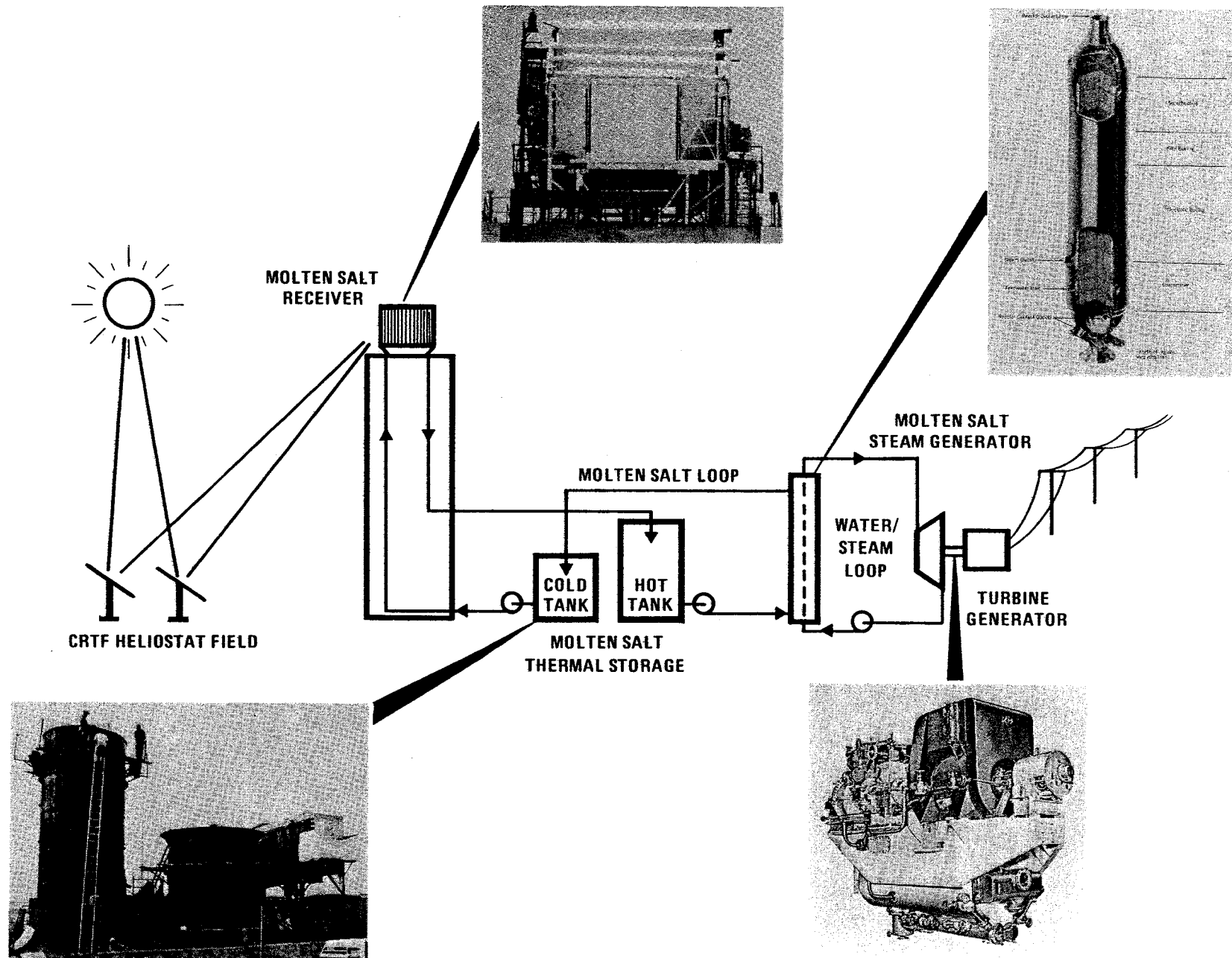


Figure 2-19. Molten Salt Electric Equipment

A three-phase program plan has been developed: Phase I covers construction and checkout of the experiment. It is estimated that the experiment will cost between \$4 and 5 million and will be completed in October 1983. In Phase II, the system will be operated and tested by utility personnel for a period of six months. In Phase III, which is optional at this time, the system will be operated for an additional two-and-a-half years in either its existing configuration or with new test hardware.

The molten salt electric experiment will benefit utilities and industry in several ways. Utilities and industry will be introduced to an advanced solar technology with hands-on operating experience. Teams of personnel from each of the participating utilities will have the opportunity to learn to operate the system, run tests, and collect data. In addition, new automatic control features for central receiver systems will be developed in the project, significantly reducing operating costs of future solar plants. Finally, this project will verify for potential lenders the soundness of advanced technology for the generation of electric power and process steam.

With funding coming from several sources, much effort was devoted in FY 1982 to establishing the management structure to coordinate the molten salt electric project. Refurbishing the molten salt receiver was nearly completed, and work to design the salt piping and steam generator was initiated.

#### C. CENTRAL RECEIVER TEST FACILITY

The Central Receiver Test Facility (CRTF), located in Albuquerque, New Mexico, is managed by Sandia National Laboratories-Albuquerque for DOE. The facility consists of a 61-m tower, 222 sun-tracking mirrors (each 37 m<sup>2</sup>), a computerized control and data acquisition system, and a video-based system for evaluating heliostat performance. Several large-scale experiments conducted at the CRTF have already been described:

- (1) Molten Salt Thermal Energy Storage SRE
- (2) Sodium-Cooled Solar Receiver Experiment
- (3) Molten Salt Electric Experiment, Phase I

Additional significant activities carried out at the CRTF in FY 1982 are described below:

##### 1. Heliostat Evaluation Program

The heliostat evaluation program at the CRTF is ongoing. In FY 1982, prototype heliostats for the 10-MWe Pilot Plant and second-generation heliostats continued to be life cycled. The life cycling of these heliostats represents an average of about 3000 cycles per heliostat. Problems experienced during life cycling include mirror module delaminations and control electronic failure. However, no structure or drive motor failures have been experienced.

The CRTF heliostat field (Figure 2-20) has been evaluated during its five years of test operation. Experience has shown that approximately 5% of the heliostats are being repaired at any one time. Major failures have included encoders and drive motors. The laminated glass facets have shown no signs of deterioration in structure or reflectivity.

## 2. Solar Furnace Completion

Construction, checkout, and initial operation of the solar furnace was completed during FY 1982. The furnace was designed to provide a high flux ( $450 \text{ W/cm}^2$ ) beam and a test stand that can be accurately positioned at the focal point. The solar furnace will provide a flux gage calibration facility in support of all solar thermal activities. The furnace also will be used for materials testing, small-scale receiver work, and small-scale chemical reactor research and development. The furnace, shown in Figure 2-21, consists of an ARCO heliostat that directs a solar beam onto a parabolic dish. The dish focuses the beam down to  $450 \text{ W/cm}^2$  peak flux, with 90% of the energy concentrated within a 13-cm-diameter area. The test table can be positioned along the three dimensions with an accuracy better than 0.13 mm. Experiments up to 450 kg can be accommodated. The shutter located between the heliostat and parabolic dish serves as a safety or pulsing device.

The major problem with the solar furnace has been disagreement among the Kendall radiometers, which are considered the standard for flux gage calibration. This problem has not yet been resolved.

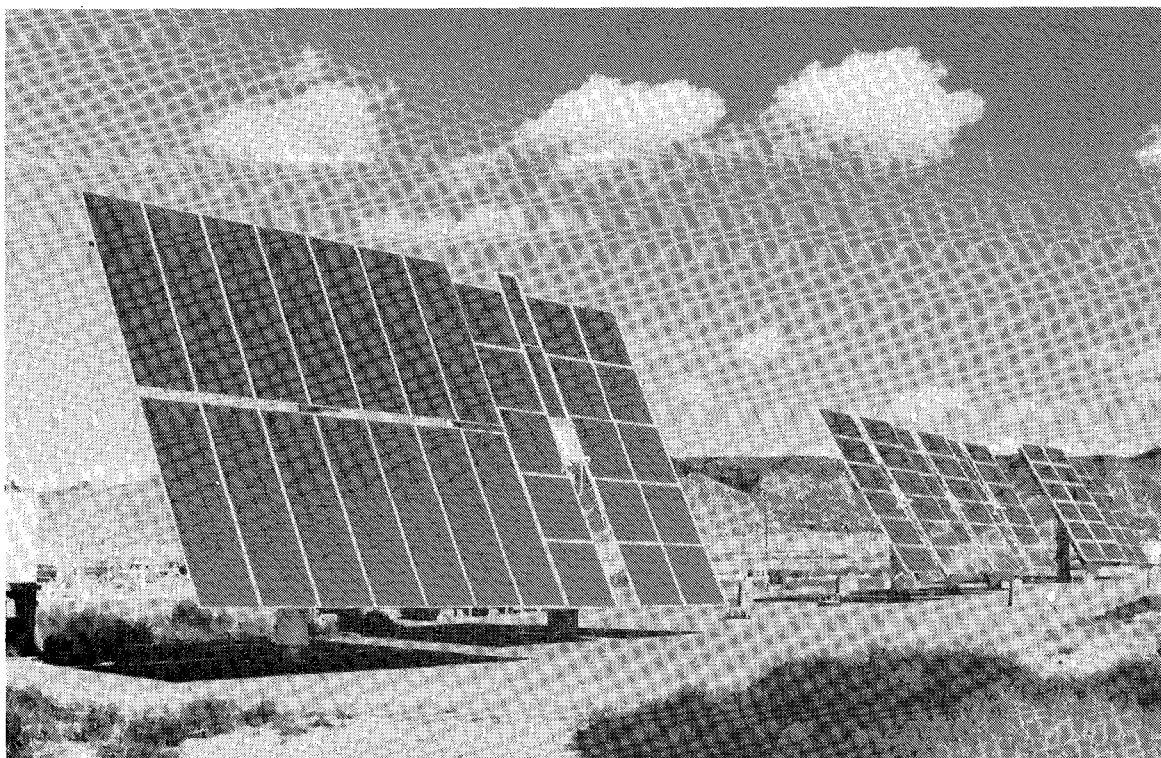


Figure 2-20. CRTF Heliostat Test Field

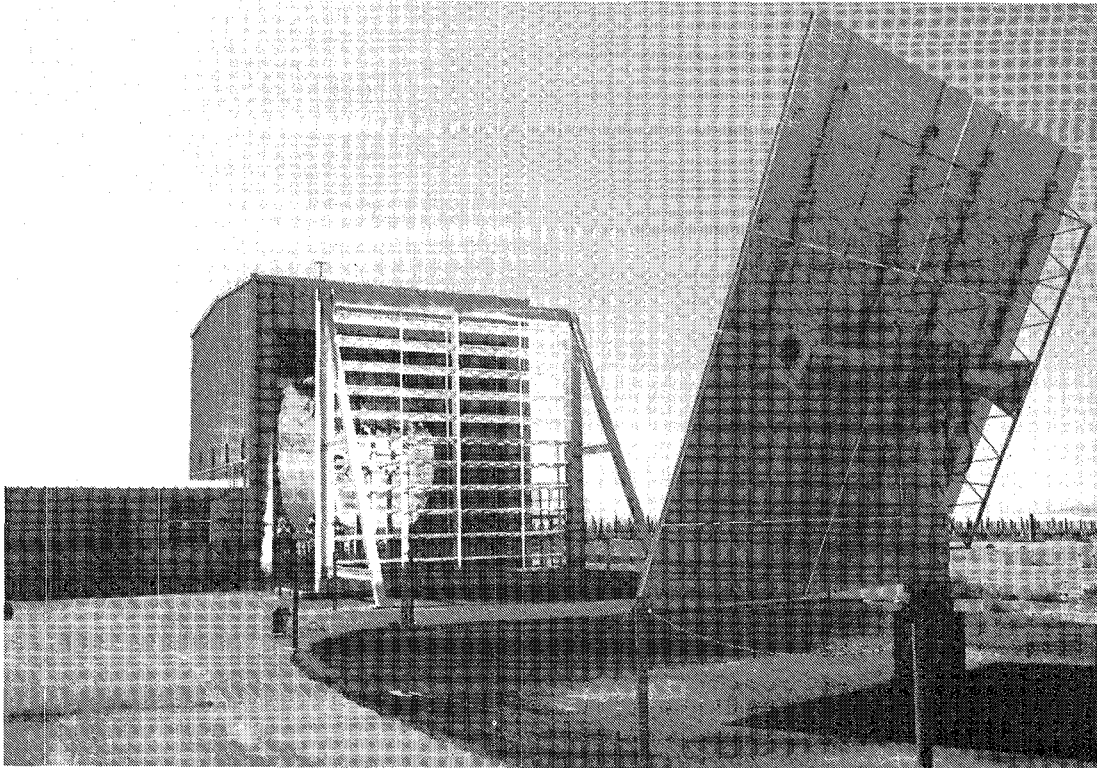


Figure 2-21. CRTF Solar Furnace

### 3. Added Capabilities

Both the solar tower and solar furnace have been equipped with fast opening and closing shutters. These shutters increase the capability of the CRTF to include pulse control of the solar flux with rise and fall time constants less than 0.5 sec. Both shutters are designed to operate within the full flux range of the tower ( $240 \text{ W/cm}^2$ ) and the solar furnace ( $430 \text{ W/cm}^2$ ).

### 4. Support of University Projects

An experimental technique was developed and hardware built and tested to measure the emissivity of copper and aluminum in air as part of a New Mexico State University graduate thesis. The solar furnace was used as the heat source, and a one-sun Kendall radiometer was used as the measuring standard. The thesis is scheduled for completion in mid-FY 1983.

Another New Mexico State University graduate thesis has involved work at the CRTF. A fluidized bed of inert sand was used in a chemical reactor to determine the effects of temperature and steam/nitrogen concentration on the production of  $\text{H}_2$ ,  $\text{CO}$ , and  $\text{CH}_4$ . The solar furnace was used as the heat source. Results currently are being analyzed; the thesis is scheduled for completion in FY 1983.

In addition, analytical designs of concentrators and redirectors for the solar tower and solar furnace were completed under a contract with New Mexico State University. These designs will be fabricated if and when demand, budget, and priority allow.



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## SECTION III

### PARABOLIC DISH TECHNOLOGY

Fiscal year 1982 was one of significant accomplishments in research and development of parabolic dish electric systems. Two modules based on different heat engine technologies provided electricity to a utility grid, and the first pre-production parabolic dish concentrator was fabricated and assembled and is now under test. In the thermal dish area, an effort was initiated in mid-FY 1982 to review thermo-optical design principles, piping field layout design concepts, reflector/structure design concepts, and mirror coatings development. Three field experiments are also being conducted to evaluate the performance of parabolic dish systems in three applications: electric power generation, cogeneration (total energy), and industrial process heat.

#### A. MODULE DEVELOPMENT

##### 1. Stirling Module Development

The Stirling dish-electric module effort was initiated by the Jet Propulsion Laboratory (JPL) in FY 1978. United Stirling AB (USAB) of Sweden was selected as supplier for the basic engine, a derivative of their model 4-95, from an ongoing automotive development program with NASA's Lewis Research Center. The power conversion assembly (PCA), consisting of a hybrid receiver (fabricated by Fairchild Stratots) integrally mated to the USAB Stirling engine (Figure 3-1), was bench tested prior to field testing on an 11-m (36-ft)-diameter test bed concentrator (TBC) at the Parabolic Dish Test Site (PDTS) in California's Mojave Desert.

In FY 1982, the Stirling PCA was installed on a test bed concentrator (Figure 3-2). The Stirling hybrid module successfully generated electricity while operating from both solar thermal power and natural gas. Tests included operating at heater head temperatures up to 770°C (1420°F), which resulted in mean engine pressures to 11 MPa (1625 psia) and solar thermal heat inputs to 20 kWt with only 20% of the TBC mirror facets uncovered. After feeding up to 15 kWe into the Southern California Edison Company's electric grid, the hybrid tests were terminated prior to performance testing because of brazing failures in the receiver heater head when 50% of the mirror facets were uncovered. Limited funds precluded the redesign and repair necessary to conduct performance tests of the hybrid system. Subsequent inspection revealed that the braze joint on the outermost heater tube had opened up due to the hot combustion gas impingement on this tube.

Following the hybrid tests, the PCA was reassembled using three similar USAB experimental solar-only receivers (ESORs). The ESOR-configured Stirling PCA module was evaluated for maximum performance, daily performance, and component performance. During a series of sunrise-to-sunset tests, the power output was in excess of 25 kWe with insolation normalized to 1000 W/m<sup>2</sup>, corresponding to a solar-to-electric conversion efficiency of 29% (from

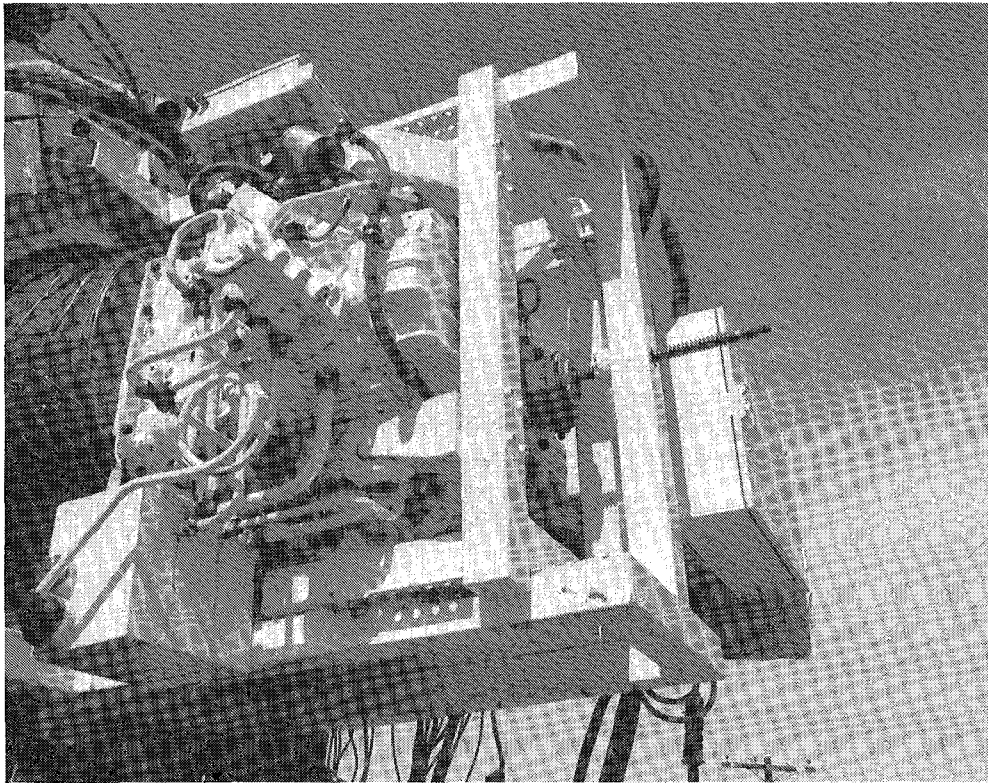


Figure 3-1. USAB-Developed "Solar-Only" Receiver and Microprocessor-Controlled Stirling Engine

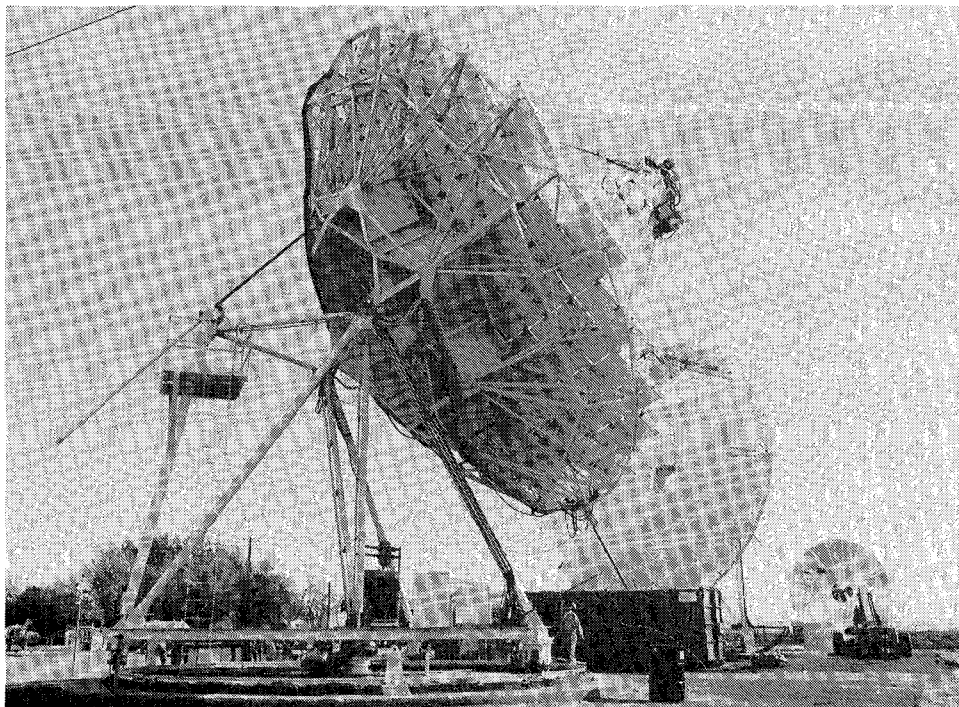


Figure 3-2. USAB Stirling Power Conversion Assembly Under Test on Test Bed Concentrator

sunlight incident on the concentrator to power out of the generator, not accounting for parasitic losses. During a two-day consecutive sunrise-to-sunset operating period, over 500 kWh of electricity was produced. Hydrogen, the engine working gas, operated at a mean temperature of 700°C (1290°F) and a mean pressure of 15 MPa (2200 psi).

As a result of a DOE Program Opportunity Notice (PON), a team of industrial and university contractors headed by Advanco Corporation entered into a cooperative agreement with DOE in FY 1982 to design, build, and test a parabolic dish-electric Stirling module, to be called "Vanguard I." The major module subsystems and corresponding responsible contractors are listed in Table 3-1.

The Vanguard team completed the conceptual design of several subsystems as well as a market assessment and sales implementation task plan in September 1982. The module conceptual design is essentially complete. All major requirements have been identified; all major system features and characteristics have been defined, and in many cases, design details have been worked out. In FY 1983, detailed design of all subsystems will be completed; hardware will be fabricated and assembled, and testing is scheduled for FY 1984.

Per contractual agreement, the module will be required to produce rated average power of 20 kWe at 480 Vac, 60 Hz at 850 W/m<sup>2</sup> direct normal insolation. It should produce net power for insolation levels as low as

Table 3-1. Stirling Module (Vanguard I) Contractors

Subsystem and Responsibility Area	Contractor <sup>(a)</sup>
Concentrator and Lead Contractor	Advanco Corporation
Engine	United Stirling AB, Sweden
Control System	Electrospace Incorporated
Generator	Onan Incorporated
General Contractor	Modern Alloys
System Integrator	Rockwell International
Site and User	Southern California Edison Company

<sup>a</sup>Other team participants include Winsmith, Rotek, Sumitomo Cycle, Corning Glass Works, and Georgia Institute of Technology.

250 W/m<sup>2</sup> and as high as 1100 W/m<sup>2</sup>, at ambient temperatures ranging from -25 to +50°C (-13 to 122°F) and wind gusts up to 13 m/sec (30 mi/h) and survive at wind speeds of up to 40 m/sec (90 mi/h). Figure 3-3 shows an elevation view of the Vanguard module; its features are listed in Table 3-2.

The Vanguard team has projected a minimum market of 50,000 units/year for the dish-Stirling modules after the economic and technical risks are ameliorated and the module is competitive with alternative sources. The allowable sales price in such a market is predicted to be \$1900/kWe. The key to commercialization is obtaining commercial sales that not only warrant higher production capacity but also provide an attractive rate of return on the investment. The latter criterion requires that an initial 1000 to 1200 units be sold at a capital cost representing two to five times that of other energy technologies. The approach for fulfilling all three criteria is using federal and state tax incentives that are uniquely available to risk-prone venture capitalists, who structure highly leveraged limited partnerships and enter into purchase power agreements with an established utility. The Vanguard sales implementation plan involves four potential primary projects and three secondary projects that could develop into commercial realities. The four primary projects represent 99 MWe of peak capacity produced by approximately 3960 Vanguard I modules.

## 2. Rankine Module Development

The organic Rankine module consists of a parabolic dish, a cavity receiver, an organic Rankine-cycle (ORC) engine with an integral permanent

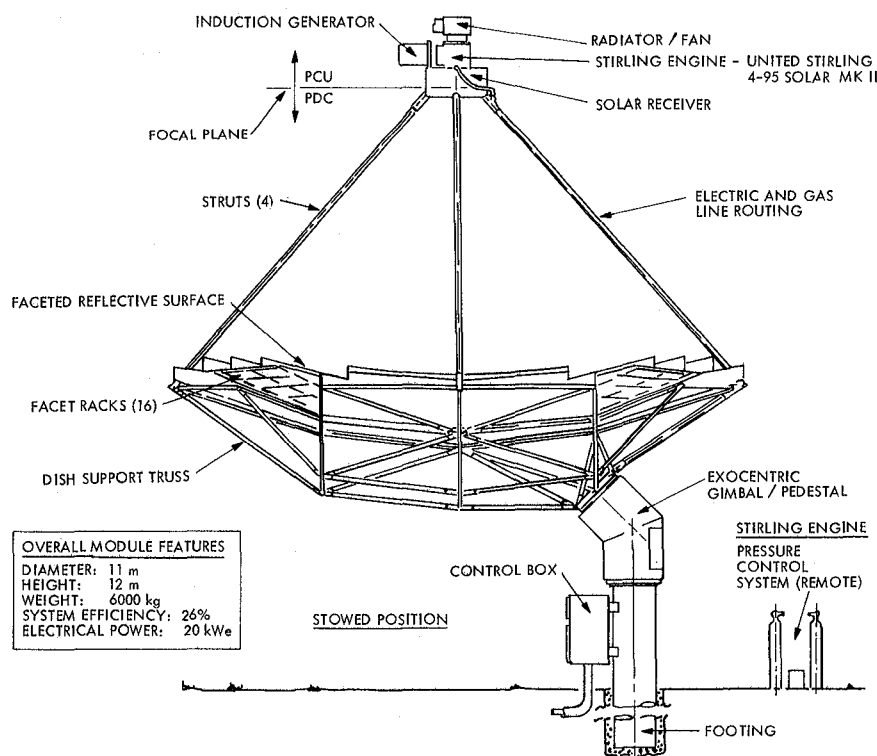


Figure 3-3. Detailed Drawing of the Vanguard Dish-Stirling Module

Table 3-2. Vanguard Dish-Stirling Module Characteristics

Feature	Details
Reflective Surface	320 facets, 460 by 610 mm (18 by 24 in.) foam-glass-backed thin glass, back-silvered mirrors with 89.2 m <sup>2</sup> (960 ft <sup>2</sup> ) total surface area
Dish Structure	Carbon steel space frame
Dish Articulation	Rockwell elevated-shoulder exocentric gimbal design
Dish Control	Electrospace model 93C-15 antenna controller and motors
Dish Pedestal	750 mm (30 in.) carbon steel pipe in poured concrete footing
Stirling Engine	United Stirling 4-95 Solar Mark II, four-cylinder with integral solar-only receiver
Generator	40-kW (30-hp) induction generator
Cooling	Dish-mounted radiator/fan combination
Working Fluid	Gaseous hydrogen
Stirling Engine Control	Mean effective pressure variation controlled via remote supply and return system

magnet alternator, and associated controls and electric power conversion equipment (Figure 3-4).

The ORC power conversion assembly (PCA) development was initiated in December 1979 with a contract to Ford Aerospace and Communications Corporation (FACC) for development of a receiver and electric power conversion equipment and system controls. FACC selected the Barber-Nichols Engineering Company to develop the engine, which uses toluene as the working fluid. This contract was expanded in 1982 to include the fabrication, assembly, and test of a parabolic dish concentrator ("PDC-1") designed by the General Electric Company.

The highlight of ORC PCA performance testing on a test bed concentrator was the module's production of over 15 kWe, which was supplied to the Southern California Edison Company's power grid. After 33 hours of operation, the PCA was removed and disassembled. Inspection revealed excessive bearing wear and

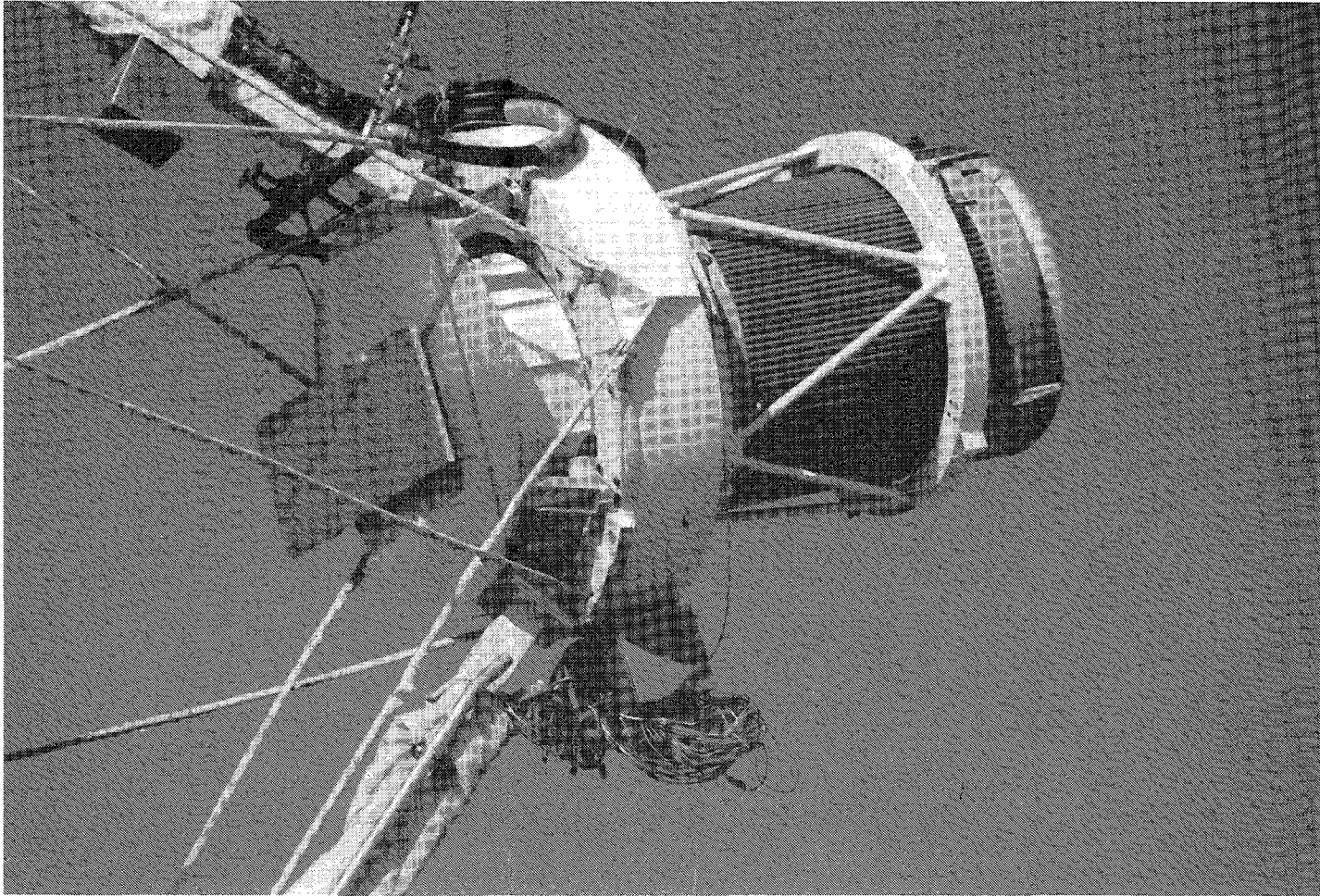


Figure 3-4. Closeup of Organic Rankine-Cycle Engine at Focus of TBC

electrical arcing between the winding and housing of the permanent magnet alternator (PMA). Work is progressing on redesign of the bearing to correct the wear problem; the PMA arcing problem is also under investigation. To help solve these problems, Barber-Nichols assembled a dynamometer test apparatus, which used a hydraulic motor driving through step-up gearing to operate the turbine/alternator/pump assembly at rated speed and electrical power output while permitting measurements to be made of torque requirements and component performance. New thrust and radial bearing configurations were also tested and qualified. The Rayleigh stepped bearing was adopted as the optimum, while alternate lubricating methods for the radial bearings were also being studied.

In spite of the bearing and arcing problems, significant milestones were reached in the development and testing of the ORC PCA. Figure 3-5 shows the PCA mounted and operating on a TBC at the Parabolic Dish Test Site (PDTs). This test series was successfully completed in March 1982. It included the electrical transport subsystem qualification of the inverter, switchboard, and power grid interconnection. The PCA operated over a complete range of test conditions, including the following:

- (1) Variable insolation levels and cloud passages
- (2) Planned and random start-ups and shutdowns
- (3) Various inverter input voltage settings (equivalent to variable turbine speed)
- (4) All control modes, control parameters, and other operating conditions

Key results of ORC performance testing are summarized below:

- (1) 33 hours of power generation over a wide range of operating and solar conditions
- (2) First demonstration of a module control system
- (3) Verification of control stability, including operation under severe transient conditions
- (4) 95% receiver efficiency at 400°C (750°F) and 980 W/m<sup>2</sup> insolation
- (5) 23% organic Rankine engine/generator efficiency
- (6) 19% efficiency from incident insolation to electricity out of alternator/rectifier (not accounting for parasitic losses)
- (7) Demonstration of inverter voltage (load) control concept for a single module and two modules (one simulated)
- (8) Excessive bearing wear
- (9) Permanent magnet alternator arcing between winding and stator



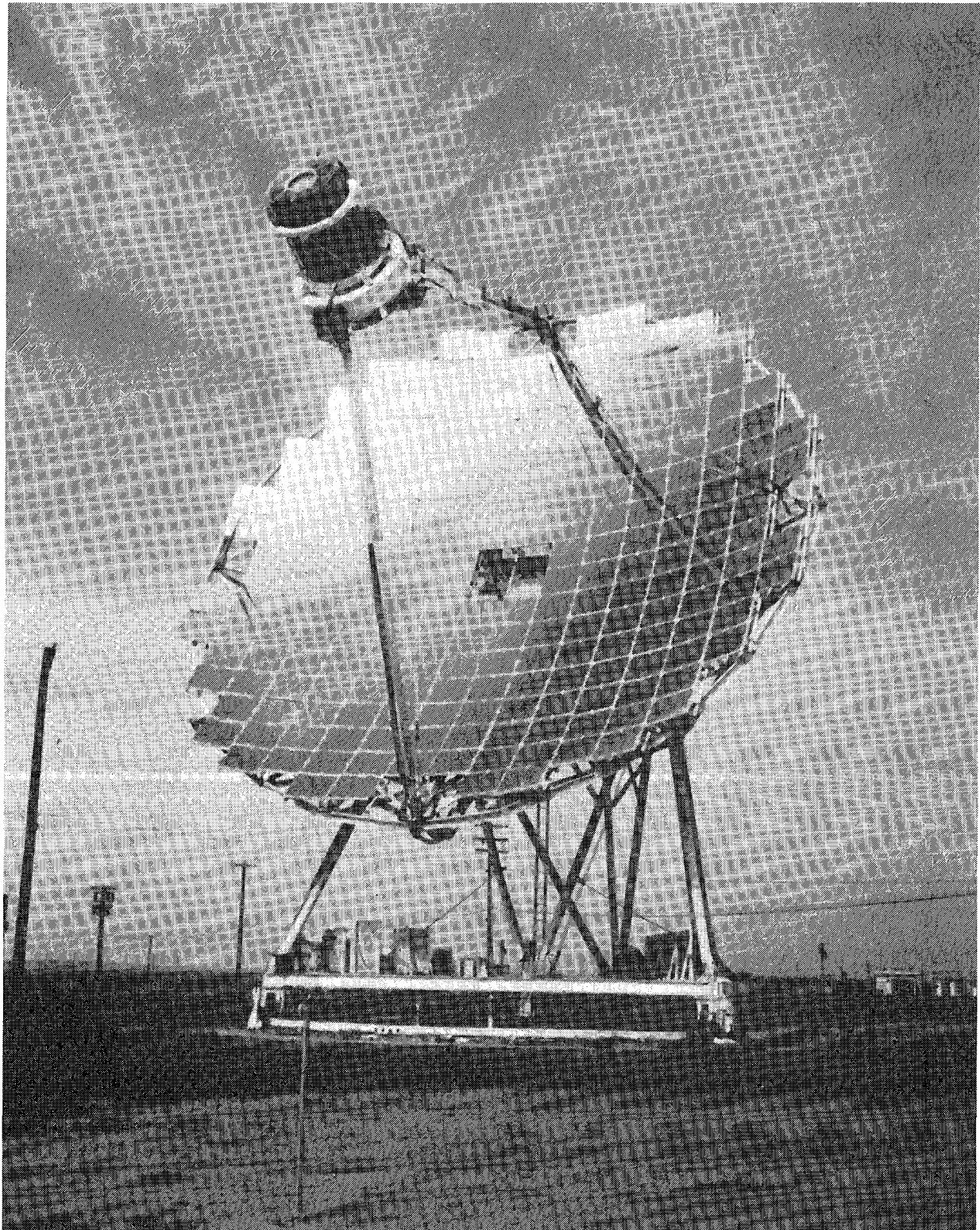


Figure 3-5. ORC Performance Testing on a Test Bed Concentrator

Figure 3-6 presents a pressure and temperature history of one ORC test when the insolation was interrupted by a series of clouds. The duration and intensity are indicated by the solar insolation plot.

A total of 33.6 hours of on-sun power generation was achieved during testing of the ORC power conversion assembly. The range of conditions tested verified the compatibility of all elements required to support a solar thermal power experiment at a small community site.

To complete fabrication of the concentrator (PDC-1) for the ORC module, FACC let contracts to Alco Machine Company for steel fabrication and to Ashland Construction Company and Valley Iron for the foundation and assembly, respectively, at the PDTIS. The reflector panels were fabricated by Design Evolution 4 under contract to JPL.

PDC-1, shown in Figure 3-7, is designed to provide 80 kWt at  $1000 \text{ W/m}^2$  insolation; its characteristics are listed in Table 3-3. The reflector panels have ultraviolet stabilized Llummar film laminated to plexiglass that is bonded to fiberglass sandwich substrates. The 36 panels are arranged in 12 gore segments, three panels per gore, and bolted to internal ribs. The base support is a tubular structure mounted on wheels; a track provides azimuth

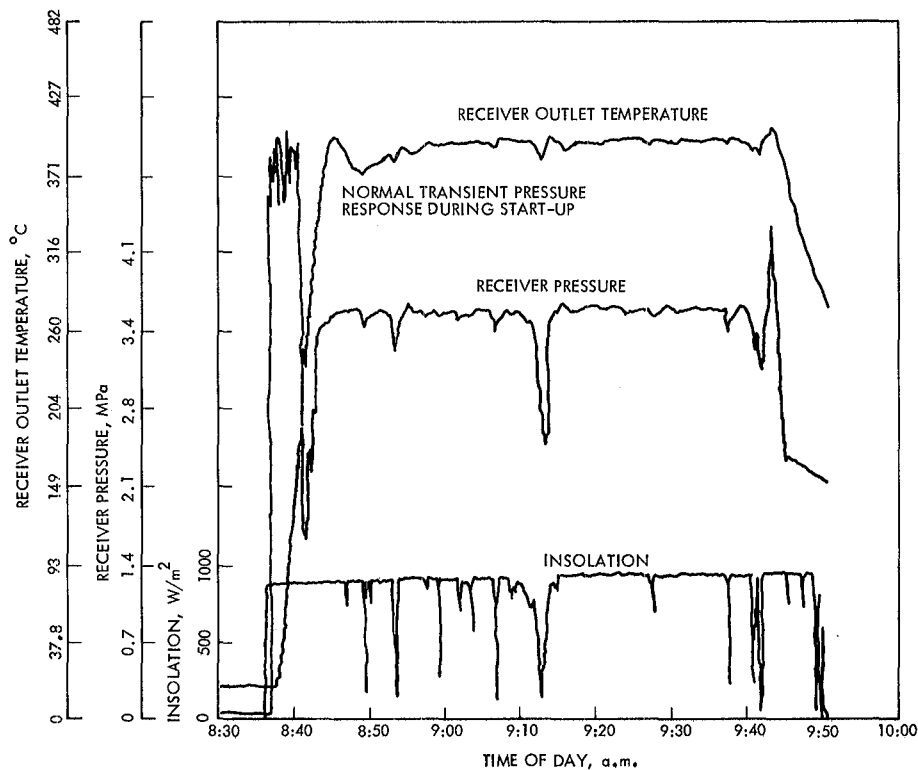


Figure 3-6. Effect of Cloud Passage on Receiver Pressure and Fluid Outlet Temperature

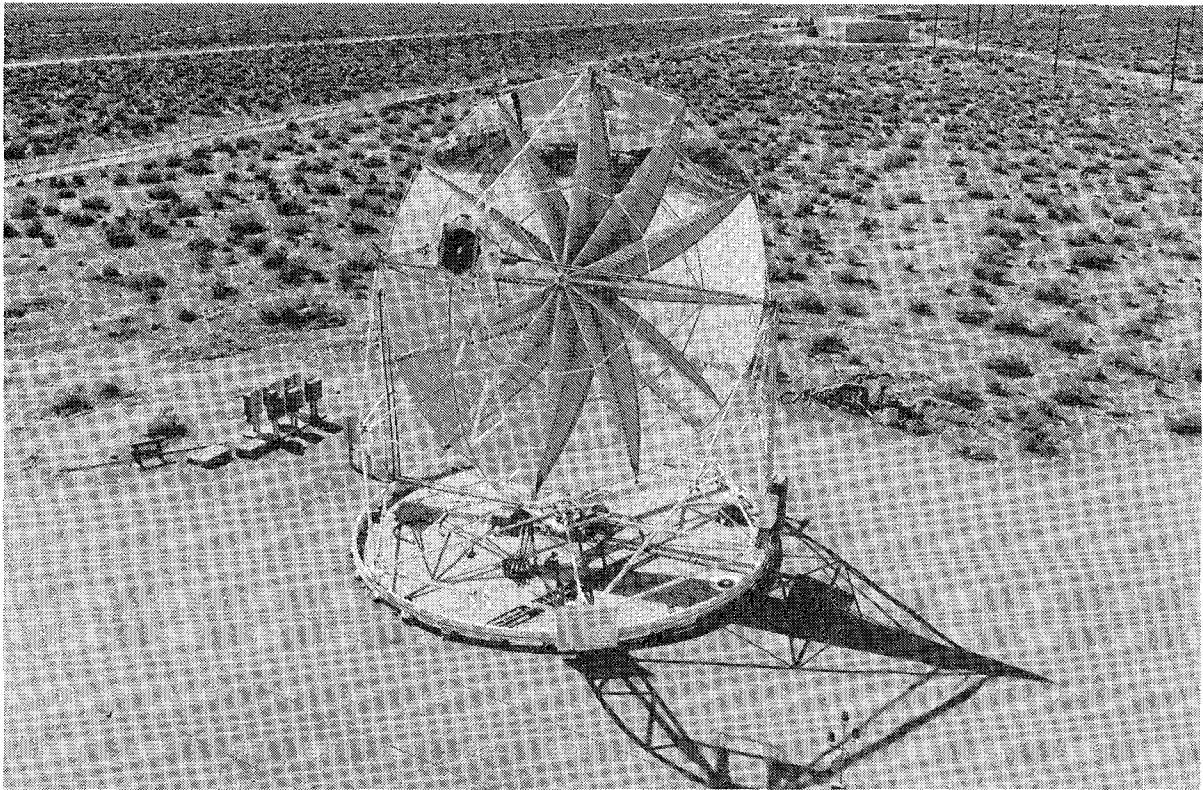


Figure 3-7. Parabolic Dish Concentrator No. 1 Installed at the PDTs

Table 3-3. Parabolic Dish Concentrator Characteristics

	PDC-1	PDC-2
Diameter	12 m (40 ft)	11 m (36 ft)
Rim Angle	53 degrees	45 degrees
Tracking Accuracy	$\pm 1/8$ degree	$\pm 1/8$ degree
Reflective Surface Area	113 m <sup>2</sup> (1216 ft <sup>2</sup> )	95 m <sup>2</sup> (1020 ft <sup>2</sup> )
Reflectivity (specular)	0.78	0.95
Concentration Ratio (geometric)	1000 for a 375-mm (15-in.)-diameter aperture	2000 for a 240-mm (9.4-in.)-diameter aperture

travel. Elevation rotation uses bearings at the edge of the dish that are supported by the base structure. Cable drive mechanisms are used for both azimuth and elevation drives.

PDC-1 performance tests are being conducted at the PDTIS. Initial tests indicate that performance should meet design specifications during completion of tests in FY 1983. Upon completion, the ORC PCA is to be mounted on the PDC-1 for module testing.

### 3. Brayton Module Development

In early FY 1982, a contract was executed with Sanders Associates to design and integrate a parabolic dish module consisting of a concentrator, air receiver, recuperated Brayton-cycle gas turbine engine with hybrid combustor, generator, and module controls. The baseline subsystems were defined as an Acurex parabolic dish concentrator (PDC-2), a Sanders air receiver, and a pair of recuperated subatmospheric Brayton-cycle (SABC) engines from Garrett AiResearch Manufacturing Company. The Sanders effort would provide the module and subsystem design and would initiate long-lead-time procurements in FY 1982 leading to fabrication, assembly, and testing of a prototype in FY 1983.

A second module with another system contractor was planned utilizing a Garrett Turbine Engine Company "solarized" advanced gas turbine (SAGT) engine. The advanced gas turbine engine is under development for the automotive industry by NASA's Lewis Research Center and would be modified for solar application.

Funding limitations permitted only a single system contract. The Sanders planning effort was redirected to include consideration of the SABC, the SAGT, and other available Brayton engine designs, but was limited to system trade studies and some preliminary design activity. In FY 1982, Acurex produced a set of unchecked drawings and specifications for PDC-2; its characteristics are listed in Table 3-3.

By March 1982, Sanders had completed trade studies of various module configurations: five candidate Brayton engines and six candidate concentrators, all using a Sanders type receiver. The systems study recommended a program that would develop two Brayton modules, which are described below:

- (1) A near-term Brayton module would be based on a single subatmospheric Brayton-cycle engine and a suitable concentrator. This engine, being developed for a gas-fired heat pump application by the Gas Research Institute, provides a near-term option with moderate efficiency and a potential near-term production base. Five Mark III development designs were fabricated, with operating test times exceeding 1000 hours. Lifetime of the engine for the heat pump program is projected at greater than 50,000 hours. This engine could be incorporated into a dish-electric Brayton module in 1984, and multi-module applications would begin in 1985. Sanders obtained data from several manufacturers privately developing concentrators that would be suitable and available for this option.

- (2) A solarized advanced gas turbine would be incorporated into a module in 1985-86 when an all-ceramic engine is scheduled to be available from the automotive advanced gas turbine (AGT) program, which will develop either the Garrett AGT-101 or a General Motors Detroit Diesel Allison AGT-100. In addition to providing high efficiency from a high-temperature engine, the automotive program has the potential for achieving the low costs associated with automobile production in the 1990's.

Sanders was also given the task of conducting a solar Brayton-cycle receiver/engine feasibility test at the PDTs with support from the Garrett Turbine Engine Company. Tests will be performed on a test bed concentrator using a power conversion assembly consisting of a Garrett Turbine Engine Company SAGT-1A engine (a metallic development version of the AGT together with ducting, gearbox, electric generator, etc.) and a Sanders receiver.

The purpose of the feasibility tests are to

- (1) Integrate and test the SAGT PCA
- (2) Obtain operational characteristics for the PCA in solar and fuel modes
- (3) Characterize the receiver

Bench testing of the metal AGT has included runs to 100,000 rev/min under load. Development problems have included:

- (1) Interference on restart due to thermal expansion caused by soak back
- (2) Intermittent dynamic stability problems in the 75,000 to 100,000 rev/min range
- (3) Excessive leakage in the rotating ceramic regenerator seals and in other joints

Some of these problems are believed peculiar to the metal engine while others must be resolved for the later ceramic engine as well. Solar testing of the SAGT at the PDTs will await more AGT testing and problem resolution.

Figure 3-8 is a photograph of an SAGT-1A engine coupled to a Sanders receiver undergoing fit and checkout tests at the Garrett facility in Phoenix, Arizona.

#### 4. Thermal Module Development

Research and development of dish collectors for thermal applications was initiated in FY 1982. Dishes provide modularity as do trough systems and can generate higher temperature process heat than troughs. The FY 1982 effort concentrated on the following: review of thermo-optical design principles, piping field layout design concepts, reflector/structure design concepts, and mirror coatings development.



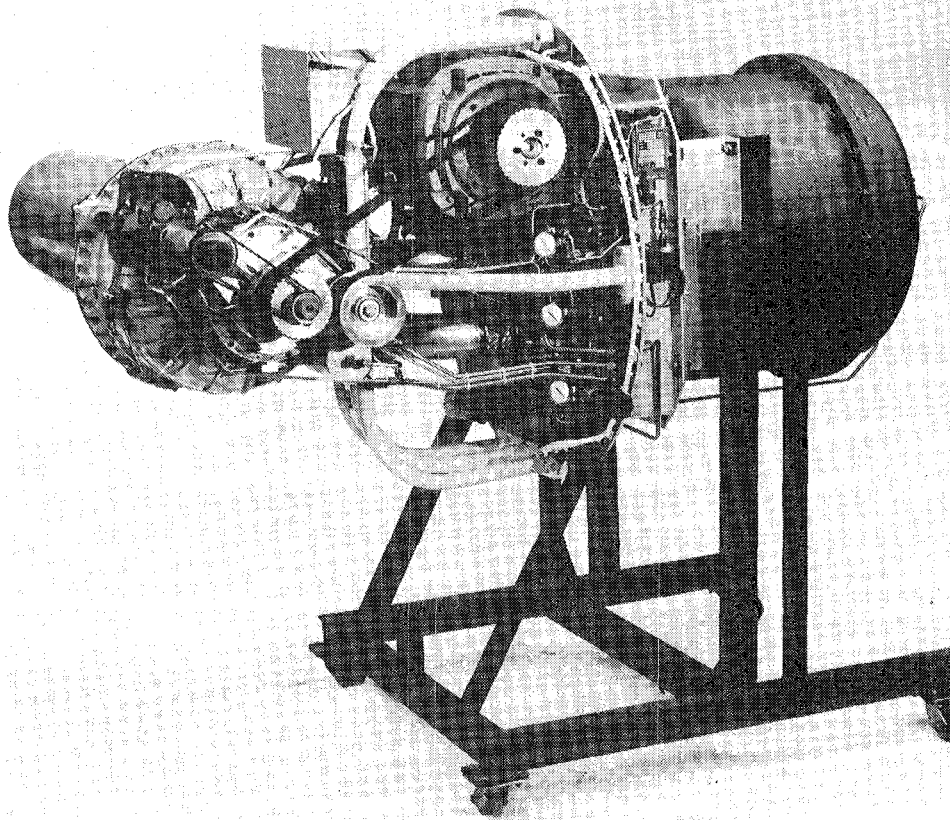


Figure 3-8. Brayton Module Power Conversion Assembly

a. Thermal Dish Piping Layout. The cost of installing a high-temperature fluid distribution system can contribute significantly to the installed cost of any solar thermal collector field. These costs can be particularly important in a large field of dishes because a fluid distribution system must be provided that connects each dish receiver to a common exit point from the field. Because plumbing costs were found to be significant in deploying parabolic trough systems, an investigation of these costs for a thermal dish field was made.

Methodology. An analysis of the piping costs associated with a field of thermal dishes comprising 50,000 ft<sup>2</sup> of aperture area was performed. The analysis was based upon the thermal dish configuration employed in the Solar Total Energy Project at Shenandoah, Georgia. (See Section III.B.2.) The analysis was performed by Jacobs Engineering Group, Inc., and was based upon a similar analysis performed as part of the trough collector development program. The system design parameters used in this study included:

- (1) Maximum heat transfer fluid flow rate = 320 gal/min
- (2) Temperature rise in heat transfer fluid = 66°C (150°F)
- (3) Maximum field outlet temperature = 316°C (600°F)
- (4) Individual dish isolation (i.e., hand valves)

- (5) Branch line isolation and control
- (6) Provision for fill and drain
- (7) ANSI piping codes
- (8) Telescoped main and branch piping headers
- (9) Nested branch piping to reduce heat loss

The temperature rise (66°C, 150°F) and maximum field outlet temperature (316°C, 600°F) was selected to allow eventual comparison with parabolic troughs. These parameters are somewhat lower than those used at Shenandoah [121 and 385°C (250 and 725°F), respectively]; however, the sensitivity of design with respect to these parameters is thought to be small (about 10%). Further analyses could be conducted to evaluate this sensitivity.

Summary of Results. The results of this analysis are summarized in Table 3-4. System parameter values were assumed and cost sensitivity was determined with respect to pressure drop in the main header piping for various header pipe sizes. Typically, low pressure drop systems

Table 3-4. Annual Operating Costs for Tubing Fluid Distribution  
(1981 Dollars)

Pressure Drop per 100 ft of Tube, ft of fluid	Annual Pumping Cost	Annual Heat Loss Cost	Pipe Costs <sup>(a)</sup>		Total Annual Operating Cost
			Capital Cost	Annual Cost <sup>(b)</sup>	
32	13,000	37,400	479,000	72,000	122,400
18	9,700	37,700	502,900	75,400	122,800
8	6,800	38,200	525,100	78,800	123,800
Excluding Dish Up and Down Comers					
32	13,000	18,500	409,500	61,400	92,900
18	9,700	18,800	432,600	64,900	93,400
8	6,800	19,300	454,800	68,200	94,300

<sup>a</sup>Includes cost for pipe, supports, anchors, and insulation.

<sup>b</sup>Annual cost = capital cost x 0.15.

are more expensive (i.e., large piping costs) but easier to control. Although both piping and tubing were evaluated, only the results for tubing are shown in Table 3-4 because its cost was about 10% lower than piping. Piping subsystem costs excluding the up and down comers from the dish receivers are also shown to allow use of the information where these items are contained within the thermal dish subsystem costs. Note that where up and down comer costs have been eliminated, the equivalent cost (assuming a 15% capital recovery factor and using per square foot of dish aperture as a basis) is approximately 12.40\$/ft<sup>2</sup>. This cost represents the thermal distribution system alone and does not include any costs associated with the electrical distribution system.

The pumping costs represent the cost of electricity (at 0.10\$/kWh) to pump fluid through the field while heat loss costs represent the value of thermal energy lost from the insulated piping. Thermal energy was valued at 10\$/MBtu. Items included in the capital cost are piping supports and anchors, tubing (or piping) and insulation. All costs were for a system located in Albuquerque, New Mexico.

b. Reflector/Structure Design Concepts. Dish collectors have demonstrated high efficiency, but to date have been relatively costly to manufacture. The next step in making them economically feasible will be to develop designs for high volume production. To this end, a study was made of production technology used in fabricating high-performance trough/reflector structures and how this technology could be incorporated in dish designs.

Methodology. Reflector structures of sizes ranging from 1 by 1 m to 2 by 6 m have been produced with manufacturing techniques commonly used in the automobile industry. These concepts include stamped sheet metal panels, sheet molding compound (SMC), sagged glass, and honeycomb (stressed skin) structures. Each of these approaches was studied for adaptation to panel production for a parabolic dish collector. The necessary changes, the advantages and disadvantages, and the trade-offs were assessed.

Three basic components of a dish are intimately interrelated; they are (a) the main structural framework of the dish that supports the reflector panels, (b) the reflector panels to which the reflector material is applied, and (c) the reflector material and its method of application. The weight of large dish structures must be minimized for several practical reasons, including cost, weight, drive power, materials limitations, and support requirements.

The dish framework must support the reflector panels while resisting gravity, wind, and snow loads. To minimize the framework, the reflector panels should contribute to the overall structural capability of the full dish assembly. There is an important synergistic effect if the reflector panel can bridge adjacent frame members; by becoming an integral part of the structure, the panel can increase the overall strength of the dish while decreasing framework requirements. To accomplish this, the reflector panel must provide some inherent strength and means of attachment to the framework.



Characteristics of the reflector material (glass, film, etc.) and method of incorporation into or on the reflector panel are critical factors in panel fabrication. The parabolic contour of the dish is nearly spherical and presents significant processing and stress problems. The leading reflector material, due primarily to its high specularity, is second-surface silvered glass. Forming glass mirrors to a dish contour is a significant engineering challenge. Approaches have included attachment of sagged (thermally formed) glass; bonding of flat, chemically-strengthened glass that is elastically formed to dish contour; use of small mirrors as in a mosaic; and use of laminated glass/steel. Secondary reflector material candidates are aluminized films, which are easier to adapt and lighter weight, but have lower reflectance and poor environmental capability.

Candidate Concepts. Most of the candidate reflector panels studied had to meet certain requirements. Several shapes of panel are usually required to fit the dish contour. Each of three or four concentric rings would have several panels in each ring with panels slightly different from ring to ring. Attachment of the panels to the framework with accurate positioning and alignment requires consideration of structural as well as fastening factors.

Candidate reflector panels are discussed below:

- (1) A stamped steel sheet metal design similar to the 1 by 2 m panels used in troughs offers several advantages. It provides a rigid steel frame panel that can easily be mounted to the steel framework. Its strength is excellent for coupling to the framework, and its thermal expansion matches; but the weight of the assembled panel is  $\sim 3.5 \text{ lbs/ft}^2$ .
- (2) An SMC panel has major disadvantages. With a low Young's Modulus and low strength, the SMC panel offers little structural capability for coupling the reflector panels to the framework, thereby increasing the required framework strength and stiffness. SMC panels would be smaller in size than the sheet metal, therefore requiring more parts per dish due to the attendant assembly and alignment costs.
- (3) Thermally formed (sagged) glass reflector panels combine panel and reflector materials. Because annealed glass has poor design strength characteristics (1000 psi), it cannot contribute to structural strength; therefore, the dish framework must be increased to totally support the glass. In addition, glass panels are heavier than other panel concepts and require more complex mounting.
- (4) Honeycomb panels have been used as the structural material for troughs, dishes, and heliostats. It has performed well as a rigid, accurate material in flat or curved sections. Large radar dishes have been constructed using radial gores of honeycomb material. Two major problems arise with honeycomb, which is typically made of steel skins and aluminum core: (1) It is very expensive to fabricate (not amenable to high volume production), and (2) it is very difficult to apply glass reflector material to a honeycomb dish panel.

From a structural view, the stamped sheet metal gore (used at Shenandoah) offers simplicity and excellent integration of the structure and the reflector panel into a lightweight dish. The structure and the panels virtually become one. The accuracy of this approach requires additional investigation for high concentration applications. Use of steel (versus aluminum) with development work to increase the stiffness and accuracy of individual panels could offer promise. The single major problem is the attachment of the reflector material to the glass. Reflective films have been used but with penalties of lower reflectance (0.81 to 0.85) and short-lived environmental capability. Application of silvered glass to stamped-panel dishes requires a major development effort.

c. Mirror Coatings Development. The long-term environmental capability of silvered glass mirrors has not been established. Generally, mirrors have not been used in outdoor installations where they must withstand severe conditions and survive with undiminished reflectance. The silver and copper layers of mirrors are painted to protect them from abrasion in shipping and handling and from corrosion in indoor environments. There had been no requirement for mirror survivability under daily outdoor conditions, nor had there been a market to justify development of a paint or coating for outdoor mirror protection.

The following requirements for mirror coatings have been developed based on experience and observation of the response of solar collector mirrors to exposure in the field and in accelerated testing in environmental chambers:

- (1) Adhere tenaciously to the copper
- (2) Provide an excellent moisture barrier, and a gas barrier for atmospheric pollutants
- (3) Be free of pinholes
- (4) Be easily applied and cured, similar to paint processes now used [curtain coat or spray; cure below 116°C (240°F)]
- (5) Provide a good surface for subsequent bonding with structural adhesives
- (6) Cause no degradation of silver either during application and cure or during long-term life
- (7) Have sufficient strength for transmitting structural loads from structure to glass

These requirements have been discussed with a broad range of personnel throughout the solar community and associated industry. Through liaison with PPG, manufacturer of one of the most widely used mirror paints, the characteristics listed above were used in a PPG program to develop a new mirror paint with improved corrosion protection. This year-long program is nearing conclusion. Mirror samples using the new paint will be available to Sandia National Laboratories-Albuquerque for evaluation.

## B. SYSTEMS EXPERIMENTS AND ANALYSES

### 1. Small Community Solar Experiment

The Small Community Solar Experiment (SCSE) was initiated in 1977 when Congress appropriated funds to build an experimental solar power plant that would be a first step in addressing the needs of the small community sector. Ford Aerospace and Communications Corporation (FACC) was selected to develop the technology for this experiment based on an organic Rankine-cycle (ORC) engine. Progress of this engine technology development is discussed in Section III.A.2 above. In FY 1982, Congress appropriated \$4 million to construct the experiment. During the course of the year, DOE decided to proceed with plans to build a 100 kWe-plant, a size considered sufficiently large to satisfy most of the technical requirements of the experiment while meeting the intent of Congress to minimize cost.

Concurrent with the development of the organic Rankine-cycle module, the process for selecting an experiment site was carried out. During FY 1982, DOE selected Osage City, Kansas, as the prime site and Molokai, Hawaii, as the alternate site. These two sites were chosen from a field of 44 communities submitting proposals. (See Figure 3-9, upper right.) Osage City is an ideal setting for the experiment (Figure 3-9) because it is representative of a large number of small cities throughout the country. It has its own generation capability, purchases power when economically advantageous, and its insolation is about average for the nation. DOE is negotiating with Osage City for a site participation agreement to be implemented in FY 1983. Preparation of the site is scheduled to begin in April 1984 and installation of the first modules in August 1984. Plant system test and operation will then start in February 1985.

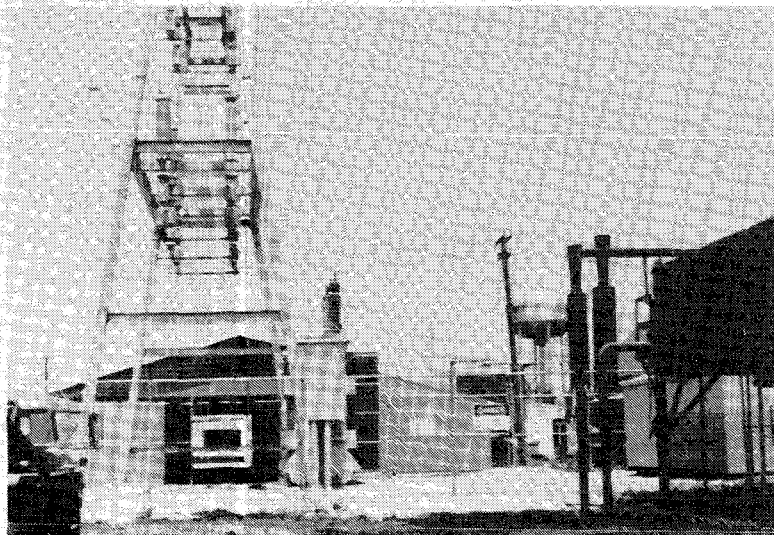
### 2. Solar Total Energy Project

The Solar Total Energy Project (STEP) at Shenandoah, Georgia, uses parabolic dishes to generate electricity, process steam, and chilled water for air conditioning. The energy is supplied to the Georgia Power Company grid and to a nearby knitwear factory owned by Bleyle of America, Inc. The objectives of this project are (1) to assess the interactions of solar total energy technology in an industrial application with an electric utility interface, (2) to acquire data for comparing cost and performance predictions, (3) to promote within industry engineering and development experience with complete solar total energy systems, and (4) to ensure that technical data are disseminated. The project encompasses design, construction, operation, and technical and economic evaluation of the solar total energy system providing power to the knitwear factory. This project is a major milestone not only for the solar thermal program, providing data to support the development of parabolic dish technology, but also for cogeneration using solar energy technology.

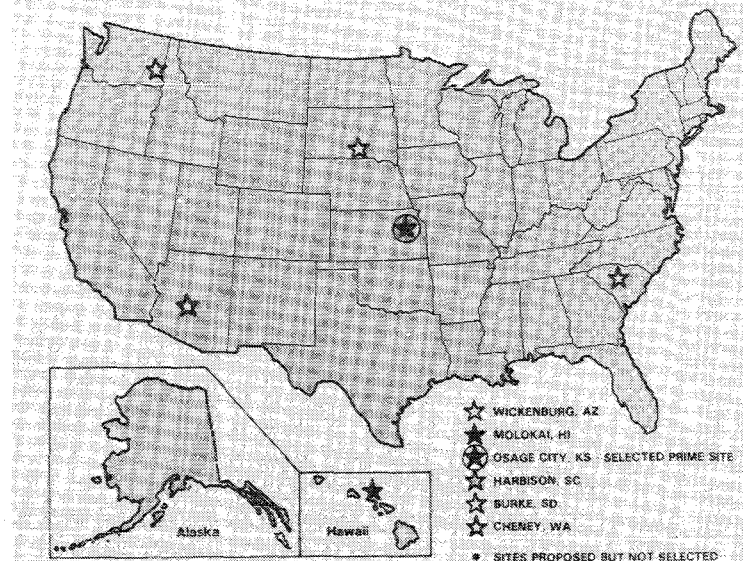
The system uses 114 parabolic dish collectors, 7 m (23 ft) in diameter, with a silicone base heat transfer fluid circulating through the receiver tubes. Solar radiation is focused on the receivers by the collectors and heats the transfer fluid to 400°C (750°F). A steam turbine provides

- MUNICIPAL UTILITY
- LOCATED IN CENTRAL U.S. – EASILY ACCESSIBLE
- 6-MWe PEAK DEMAND
- LOCAL GENERATION FROM DIESEL OR NATURAL GAS – 10-MWe PEAK CAPACITY
- FIVE UNITS: 1–2.8 MWe EACH
- PURCHASE POWER FROM KANSAS POWER AND LIGHT IN WINTER
- SERVES A POPULATION OF 2800
- NUMBER OF EMPLOYEES: 8 PLUS LINE CREW

### EXISTING PLANT



### SCSE SITE SELECTION



### NEW SITE

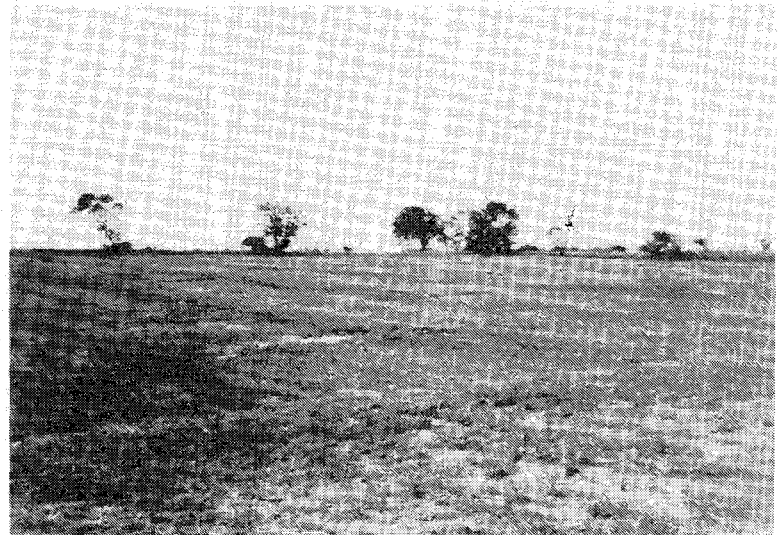


Figure 3-9. The Small Community Solar Experiment, Osage City, Kansas

400 kW of electrical energy; the steam is extracted from the turbine at 180°C (356°F) for knitwear processing. Exhaust steam at 115°C (239°F) is used to provide thermal energy to chill water for air conditioning.

Collector installation was completed by Solar Kinetics, Inc., during the first quarter of calendar year (CY) 1982, and acceptance testing was concluded in the second quarter. Figure 3-10 shows a row of collectors in operation. The effects of the moist Shenandoah environment on the components became evident during the acceptance tests; hence, drive motors, position indication potentiometers, and resistance temperature devices were refurbished to resist humidity so that collector operation would not be compromised.

Installation of the equipment for the balance-of-plant was completed during the second quarter of FY 1982, and steam was generated with the fossil fired heater supplying the energy to the heat transfer fluid. This steam was supplied to the Bleyle plant for process use. Electrical power generation began in the third quarter, and a total of 17,852 kWe-h was generated in FY 1982. A diagram of the system is shown in Figure 3-11.

Provisional acceptance of the total system occurred and the plant dedicated on May 10, 1982. In Figure 3-12, DOE Deputy Assistant Secretary for Renewable Energy, Robert San Martin, is shown addressing the crowd at the dedication ceremony. The operational phase of the project was also initiated

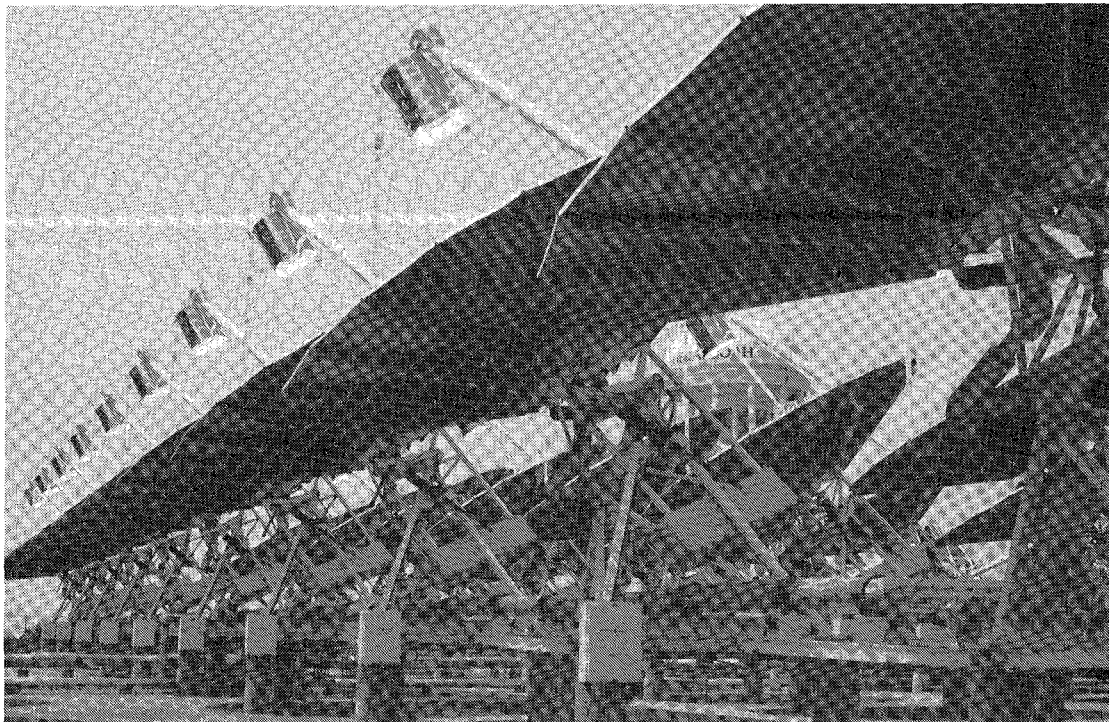


Figure 3-10. One Row of Parabolic Dish Collectors in Operation at the Shenandoah Solar Total Energy Project

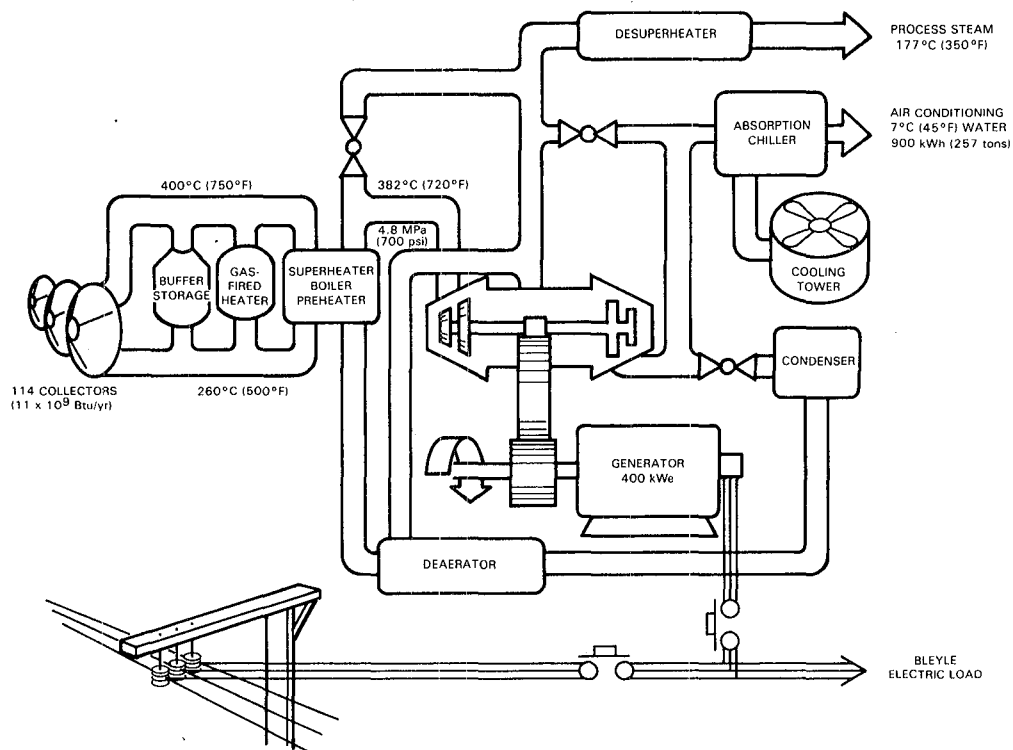


Figure 3-11. Schematic Diagram of the Solar Total Energy Project, Shenandoah, Georgia



Figure 3-12. Shenandoah STEP in Operation During Dedication Ceremony, May 10, 1982



during the third quarter although demonstration of the various operational modes of the system had to be postponed because of computer limitations. A larger capacity computer was procured to rectify this deficiency.

Georgia Power Company personnel, who will operate the plant, were in training during the third quarter and assumed this activity in the fourth quarter. The Georgia Power/DOE cooperative agreement for site operation was consummated during the fourth quarter. The plan calls for two years of formal operation under the agreement followed by an additional two years of independent operation by Georgia Power, during which time operating data will be supplied to DOE.

During the fourth quarter, computer controlled operation of the collector field was achieved. Figure 3-10 shows these collectors tracking automatically. During this all-day operation, 1800 kW of thermal energy was supplied. A peak steam flow rate of 9000 pounds per hour was established, from which 600 ton-hours of air conditioning and 800 pounds per hour of process steam at 100 psi was dissipated in the condensor. Energy production during FY 1982 from both solar and fossil heater sources totaled 18 MWh of electricity, 22,000 ton hours of air conditioning, and 244,000 pounds of process steam.

During the same quarter, system operation of the site was curtailed due to continuing problems with cavitation of the heat transfer fluid (HTF) pumps. The problem was traced to water ingestion from breaks in the superheater tube bundle of the steam generator. The breaks, which are being repaired, are thought to be the result of thermal stress created by circulating "cold" heat transfer fluid from the collector field through the hot tube bundle of the steam generator. This procedure has been modified to minimize such thermal shock. Renovation of the fossil-fired heater is underway to insulate the heating section. Repairs are also being made to the fiber-optic circuits in several collectors to improve the closed-circuit tracking capability of these collectors.

With upgrading of the computer, repairs to the steam generator, renovation of the heater, and improvements to the collector tracking system, plant operation in FY 1983 should be possible on a continuous, consistent basis.

### 3. Capitol Concrete Experiment

a. System Description. A parabolic dish collector, manufactured by Power Kinetics, Inc., and installed by Applied Concepts Corporation, was constructed at Capitol Concrete Products in Topeka, Kansas (Figure 3-13). The engineering experiment was conducted to determine the technical feasibility of using the PKI Fresnel point-focusing collector to provide process steam in an industrial environment -- in this case for the curing of concrete blocks.

The concentrator consists of 864 square mirrors 0.305 by 0.305 m (1 by 1 ft) mounted on 108 identical curved modular support assemblies attached to a lightweight space-frame structure of steel tubing members and steel plate



Figure 3-13. The Power Kinetics Collector in Operation at the Capitol Concrete Block Plant in Topeka, Kansas

joints. The  $80\text{-m}^2$  ( $864\text{-ft}^2$ ) array, approximately 9.1 m (30 ft) high and 10.4 m (34 ft) wide, is mounted on a 7.3-m (24-ft)-diameter steel track. The track rests and rotates on eight casters mounted on a foundation provided by Capitol Concrete.

The dual-axis tracking concentrator focuses sunlight on the receiver throughout the day. Tracking is accomplished by rotating the collector track on its casters for azimuth and simultaneously rotating each mirror support assembly around its center of gravity for elevation.

The concentrator focuses sunlight on a cavity receiver consisting of a parallel tube boiler, a flux trap, and a fiberglass board-insulated galvanized steel housing. The 11-m (36-ft) boom supporting the receiver at the focal plane is hinged at the concentrator base for easy access and stabilized with guy wires. A piston pump supplies boiler water from a feed tank at a maximum pressure of 1.0 MPa (150 psi). Capitol Concrete supplies ambient temperature treated water or hot condensate to the feed tank. Steam at 0.67 MPa (100 psi) is provided to Capitol Concrete via a rotating union connector at the collector base.

A microcomputer control subsystem accepts feedback control signals through shadow-band sensors mounted on the collector. Stored sunrise and sunset data permit start-up, shutdown, and tracking during cloud cover. Sensors also detect maximum allowable wind gust speeds, lack of sun for ten



minutes, and collector malfunctions that direct the microcomputer to stow the collector mirrors in an inverted position. Automatic fluid loop drain-down is commanded for fluid temperatures below 4.5°C (40°F). The control system operates from a trickle-charged dc battery, assuring operation in the event of a power failure.

Preliminary collector test results of a similar unit installed at the Sandia National Laboratories' Mid-Temperature Systems Test Facility in Albuquerque, New Mexico, showed an approximate efficiency of 80% at 980 W/m<sup>2</sup> insolation, or about 60 kilowatts of thermal energy (60 kWt).

b. Operational Phase. After completion of installation at Capitol Concrete Products, a two-week supervised operational test was conducted during July 1982, and a two-day acceptance test was completed during August. The total availability of the plant has been above 80% from July 16, 1982, through the end of September.

Several technical problems have been identified and addressed during checkout and the short operating period. One such problem consisted of loss of focus accuracy early and late in the day. This condition was improved by adjustments in the tilt angles and drive linkage, but further development work is needed to acquire the sun near the horizon. Another problem was caused by failure of the water level sensor, which allowed the receiver to run dry and overheat. Repairs were effected, and a redundant sensor was added to the system for reliability. A series of start-up problems with instrumentation and data acquisition equipment has resulted in a less-than-expected accumulation of credible data.

The DOE contract with Applied Concepts for operation and data collection will end in November 1982, after which ownership and operational responsibility will be assumed by Capitol Concrete Products.

### C. PARABOLIC DISH TEST SITE

The JPL Parabolic Dish Test Site at Edwards Air Force Base, California, is shown in Figure 3-14. It features two test bed concentrators (TBCs) and a newly installed prototype concentrator, Parabolic Dish Concentrator No. 1. The two TBCs, 11 m (36 ft) in diameter, providing 78 kWt at the focal plane with 1000 W/m<sup>2</sup> insolation, continued to prove their worth with excellent reliability throughout the year. The TBCs were used as test vehicles to characterize three power conversion assemblies: a solar/hybrid Stirling, a solar-only Stirling, and an organic Rankine-cycle. Because of their excellent optical characteristics, the TBCs were also used at night to detect high energy gamma radiation.

FY 1982 activities at the Parabolic Dish Test Site are detailed below:

- (1) Initiated and completed a series of tests of the solar/hybrid Stirling power conversion assembly on TBC-2. Net power was delivered to the Southern California Edison (SCE) grid.

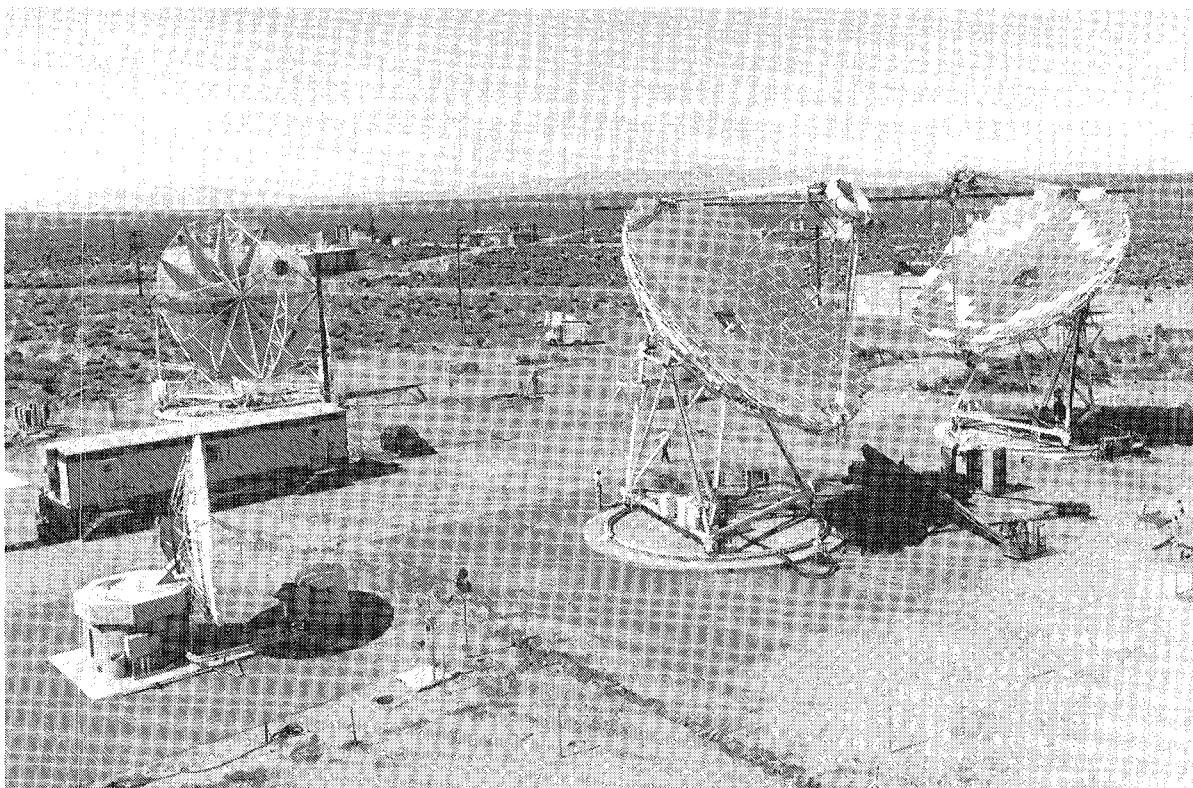


Figure 3-14. Parabolic Dish Test Site, Edwards, California

- (2) Initiated and completed a series of tests of the organic Rankine-cycle power conversion assembly on TBC-1. Up to 16 kWe was generated with a solar-to-electric conversion efficiency of 20%, not accounting for inverter and parasitic losses. The power was delivered to the SCE grid. The engine uses toluene as a working fluid and is described in Section III.A.2 above.
- (3) Initiated and completed a series of tests of a Stirling power conversion assembly using solar-only receivers on a TBC for United Stirling AB. Three different solar receiver designs were coupled to the Stirling engine during these tests. 25 kWe was generated with a solar-to-electric conversion efficiency of 29%, not accounting for parasitic losses. This power was delivered to the SCE grid.
- (4) Conducted calibration tests on both TBCs for concentrator characterization and for providing specific power levels for a particular experiment or test usage. Mirror realignment was performed to support the solar-only testing of the Stirling power conversion assembly. A cavity calorimeter and a flux-mapper were used for characterization.
- (5) Installed a Gortrac cable and hose carrier system on each TBC, removing virtually all stresses on the cables and hoses during azimuth motion of the TBCs. The carrier significantly increases the operational life of the cables and hoses.

- (6) Installed a backup slewing system on each TBC using a 1.5 hp air motor for moving the concentrators off-sun in the event of a commercial power failure.
- (7) Installed a TV camera on each TBC. The four center mirrors, which had little or no input to the concentration because of shading from the PCA, were removed in order to install the camera. The camera provides safe direct observation of the concentrator focal plane while slewing on- and off-sun and during testing.
- (8) Moved an Eppley pyrhelimeter from a ground-mounted location onto each TBC for observing the same insolation as the concentrator, which provides a more accurate assessment of concentrator performance. The pyrhelimeters were positioned on the low side of the dishes, permitting accurate boresighting while the concentrator is on-sun.
- (9) Initiated and completed a series of tests to detect high energy gamma radiation being emitted from various celestial objects. Dr. Richard Lamb, Professor of Physics at Iowa State University, used both TBCs during these nighttime tests. The technique utilized photomultipliers mounted at the focal plane of each TBC, which were pointed accurately (and simultaneously) at the celestial object to be observed. Drift scans were employed for the observation and recording of data.
- (10) Initiated a series of material tests on TBC-1 to identify aperture material that could withstand sun walk-off as well as normal slewing on and off the sun.
- (11) Installed a 12-m (39-ft)-diameter prototype dish at the site. Checkout of this dish, designated Parabolic Dish Concentrator No. 1 (PDC-1), has been initiated.

## SECTION IV

### PARABOLIC TROUGH TECHNOLOGY

Activities in FY 1982 brought the parabolic trough development program closer to achieving durable, high-performance, low-cost designs of modular trough systems. Component and subsystem projects included the performance prototype trough and components developed under the DOE line-focus Program Research and Development Announcement (PRDA). Continuation of operating systems experiments and completion of construction of new pilot installations are demonstrating the ability of trough systems to meet electrical and process heat requirements of agriculture and industry. These systems experiments encompass the 150-kWe Irrigation Project in Coolidge, Arizona; the Modular Industrial Solar Retrofit Project; the Small Solar Power Systems Project in Almeria, Spain; and a number of DOE-sponsored industrial process heat projects throughout the United States.

#### A. COMPONENT AND SUBSYSTEM DEVELOPMENT

##### 1. Performance Prototype Trough

The Performance Prototype Trough (PPT) Development Project began in 1979 to apply information gained from the development of previous first-generation parabolic trough collectors. The goals were to improve peak performance to 60% (from the 40 to 56% achieved by first-generation troughs) at 300°C (572°F) and to increase durability and component life to 20 years. First-generation designs did not lend themselves to mass production, a feature necessary for achieving low cost; therefore, the subsequent effort emphasized designs that use mass-production materials and processes.

In 1980, an engineering prototype trough, which achieved 60% peak efficiency, was developed. At the same time, different manufacturing concepts to adapt trough designs to mass-production processes were being investigated. Controls, drives, pylons, foundations, plating, and four different structural designs were obtained from industry. Prototypes of the designs were fabricated from soft tooling and evaluated. The final step in the Performance Prototype Trough Project was the assembly of four designs into 24-m (80-ft) drive strings in FY 1982, integrating them in a  $\Delta T$  string with a tracking and control system, and performing system tests (Figure 4-1). The technology developed will be transferred to industry via conference presentations in early 1983. Evaluation of improved tracking system designs and materials will continue in FY 1983.

The following sections summarize work performed on this project during FY 1982.

a. System Description. The PPT system consists of four individual 80-ft long drive strings, each using a reflector structure design based on a different mass production technology. All other parts of the individual drive strings are identical. The four mass production technologies used for fabrication of the reflector structures are:

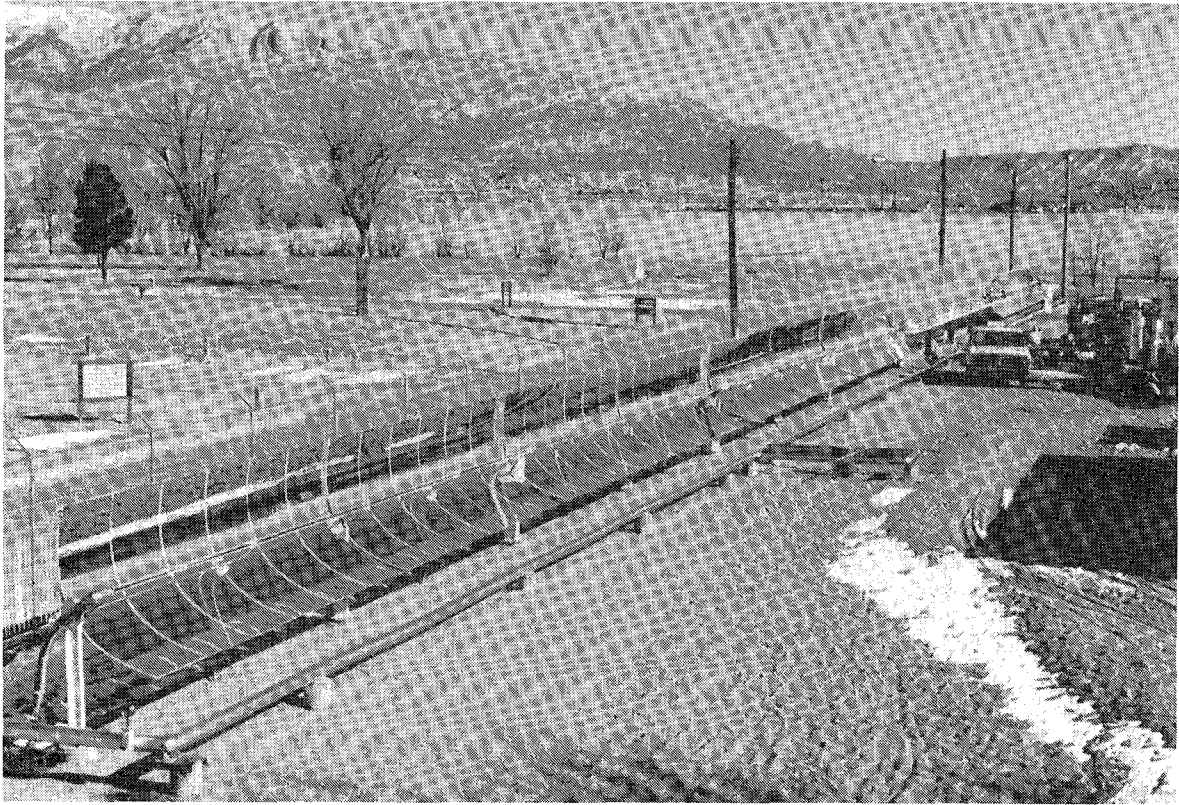


Figure 4-1. PPT Collector  $\Delta T$  String Installed at the Test Site

- (1) Stamped sheet metal
- (2) Sheet molding compound
- (3) Sagged glass/steel frame
- (4) Honeycomb sandwich

Prototypes of each reflector structure were fabricated and environmentally evaluated prior to fabrication of the PPT system.

Most of the critical components of the PPT collector system were fabricated through industrial contracts. Sandia National Laboratories-Albuquerque was responsible for specification, evaluation, integration, and systems engineering of the industrial fabricated components. Table 4-1 lists the major component suppliers.

b. Test Results. Collector field layout studies during FY 1981 by the Jacobs Engineering Group resulted in a preliminary design for a  $4645\text{-m}^2$  ( $50,000\text{-ft}^2$ ) parabolic trough collector field. The PPT collector test system is installed so that it represents one of the  $\Delta T$  strings of the design, particularly in the areas of pipe layout, electrical layout, foundations, control, and emergency power. Figure 4-1 is a photo of the PPT collector  $\Delta T$  string installed at the test site. The  $\Delta T$  string is 320 ft long and contains  $192\text{ m}^2$  of collector aperture area.

Table 4-1. PPT Major Component Suppliers

Component	Supplier
Reflector Structure Assembly:	
Stamped Sheet Metal	Budd Company
Sheet Molding Compound	Budd Company
Sagged Glass/Steel Frame	Budd Company
Honeycomb Sandwich	Parsons of California
Reflector Structure Mirrors	Corning Glass and Schott America Glass
Pylons	Bloomer-Fiske, Inc.
Foundation	Applied Research Associates
Torque Tube	Budd Company
Insulated Metal Hoses	Hydroflex Company
Black Chrome Selective Coating	Highland Plating Company
Drive	Cleveland Gear/Winsmith, Inc.
Control	Honeywell Corporation
Field Layout Design	Jacobs Engineering Group
Test Site Design	Black & Veatch Engineers
Wind Load Definition	Colorado State University
Receiver Glazing	Corning Glass Company

Performance testing was conducted during FY 1982. Nominal design and test conditions for the PPT collector system are listed below:

- (1) 232°C (450°F) input temperature
- (2) 316°C (600°F) output temperature
- (3) Therminol-66 heat transfer fluid
- (4) 66°C (150°F) temperature rise in 320 ft of active collectors

(5) East/west orientation

System testing was conducted in the following general areas:

- (1) Noontime (peak) efficiency to 316°C (600°F)
- (2) All-day efficiency: solstice and equinox
- (3) Drive system accuracy
- (4) Computer versus shadow-band versus integrating wire tracker
- (5) Automatic control: fluid control, system software, emergency power, and tracking
- (6) Best focal location for receivers
- (7) Receiver tube heat loss to 316°C (600°F)
- (8) Optimal start-up/shutdown operating philosophy
- (9) System pressure drop tests

Table 4-2 presents noontime system performance under nominal operating conditions. Figure 4-2 presents the noontime efficiency versus operating temperature at a 1000 W/m<sup>2</sup> sun level for all four 80-ft-long drive strings. Table 4-3 presents the all-day performance for the system operating under typical process heat conditions. The input temperature is constant at 177°C (350°F) and the flow rate is held constant, resulting in a variable output temperature [flow rate calculated to provide 260°C (500°F) fluid at noon].

Table 4-2. PPT Test Summary. Heat Transfer Fluid at 232°C (450°F) In and 316°C (600°F) Out, with Insolation at 1000 W/m<sup>2</sup>

	Noontime Efficiency, %	Operating Range, °C (°F)
Collector A (Sandwich)	68.0	232 - 253 (450 - 488)
Collector B (SMC)	64.7	253 - 274 (488 - 525)
Collector C (Glass/Truss)	65.8	274 - 295 (525 - 563)
Collector D (Sheet Metal)	64.8	295 - 316 (563 - 600)
Collector ABCD Average	65.8	232 - 316 (450 - 600)
ΔT String Efficiency <sup>(a)</sup>	64.2	232 - 316 (450 - 600)

<sup>(a)</sup> Includes losses of all flex hoses and lead in/out piping.

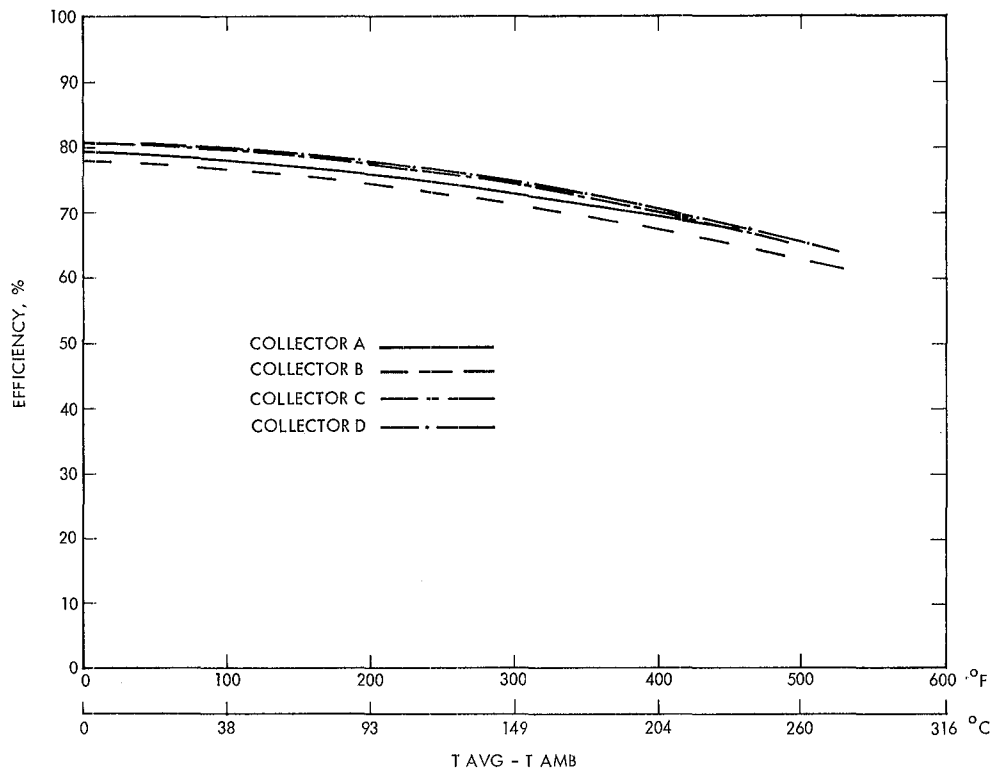


Figure 4-2. PPT Collector Efficiency

Table 4-3. PPT All-Day Performance (Equinox; March 24, 1982)

	Energy, kWt-h	Efficiency, <sup>(a)</sup> %
Collector A (Sandwich)	224	64.9
Collector B (SMC)	213	61.3
Collector C (Glass/Truss)	212	61.0
Collector D (Sheet Metal)	211	60.7
Collector ABCD Average	860	61.9
$\Delta T$ String	835	60.1
Sun (Direct Normal Incident)	1799	-
Sun (Available to One-Axis- Tracking East/West Collector)	1390	-

<sup>(a)</sup>Efficiency based on 1390 kWt-h available to PPT collector.



## 2. Component Development

Development of trough system collectors and components continued in FY 1982 under a DOE PRDA (Program Research and Development Announcement). The effort concentrated on improving thermal performance, achieving greater durability and reliability, and developing mass-producible modular units that can be installed with a minimum of field labor and construction equipment. The PRDA was issued in 1980 to accelerate the development of mass-producible collectors by manufacturers of existing trough collector systems, and to give collector component manufacturers the opportunity to develop an improved product that can be mass-produced. The 1985 goals for these systems are:

- (1) Peak thermal performance: 71% efficiency at 205°C (400°F); 65% efficiency at 315°C (600°F)
- (2) Cost before installation: 100\$/m<sup>2</sup> (10\$/ft<sup>2</sup>) in 1980 dollars at 500,000 m<sup>2</sup> (5,000,000 ft<sup>2</sup>) per year
- (3) Lifetime: 10 to 20 years

Cost-sharing contracts were awarded in early FY 1981 to Acurex Corporation for collector development, tracker development, and control system development; to Solar Kinetics and Suntec Systems for collector development; and to Winsmith for gear drive development.

a. Acurex Collector, Tracker, and Control Development. The Acurex collector design consists of a structural torque tube with welded flanges at intervals along its length to which sheet metal ribs are riveted. Laminated glass/steel reflector panels, which extend from rim to rim, are mechanically clamped at the rib edge to retain the accurate parabolic contour of the ribs. Six collector modules comprise the 36.5-m (120-ft) drive string, which was fabricated and installed at the Acurex plant in late CY 1981. (See Figure 4-3.) Performance testing was completed in mid-FY 1982, and a draft final report was submitted; the final report was approved, incorporating minor technical comments by Sandia National Laboratories-Albuquerque (SNLA) and DOE Albuquerque Operations Office (ALO). Test data indicate efficiencies of about 55 to 60% with output temperatures between 260 and 316°C (500 and 600°F).

The tracker and controller system developed by Acurex integrates those functions into a mass-producible design that features the following:

(1) fail-safe logic requiring only auto-track, hold, or stow commands, (2) tracking light sensor on a single chip, (3) control interface using telephone-tone technology hardware, and (4) incorporation of a solar tracking angle reference (STAR) system that senses coarse sun position and insolation level to direct the tracker controller, which then tracks for the entire field.

Production design units were fabricated in FY 1982, and integrated testing of the tracker and drive string was performed at Acurex. Modular controller units were fabricated, with integrated testing using the drive string scheduled for early FY 1983. In-service and performance evaluation of the tracker controller system will be conducted in FY 1983 when the MISR unit is installed at SNLA.

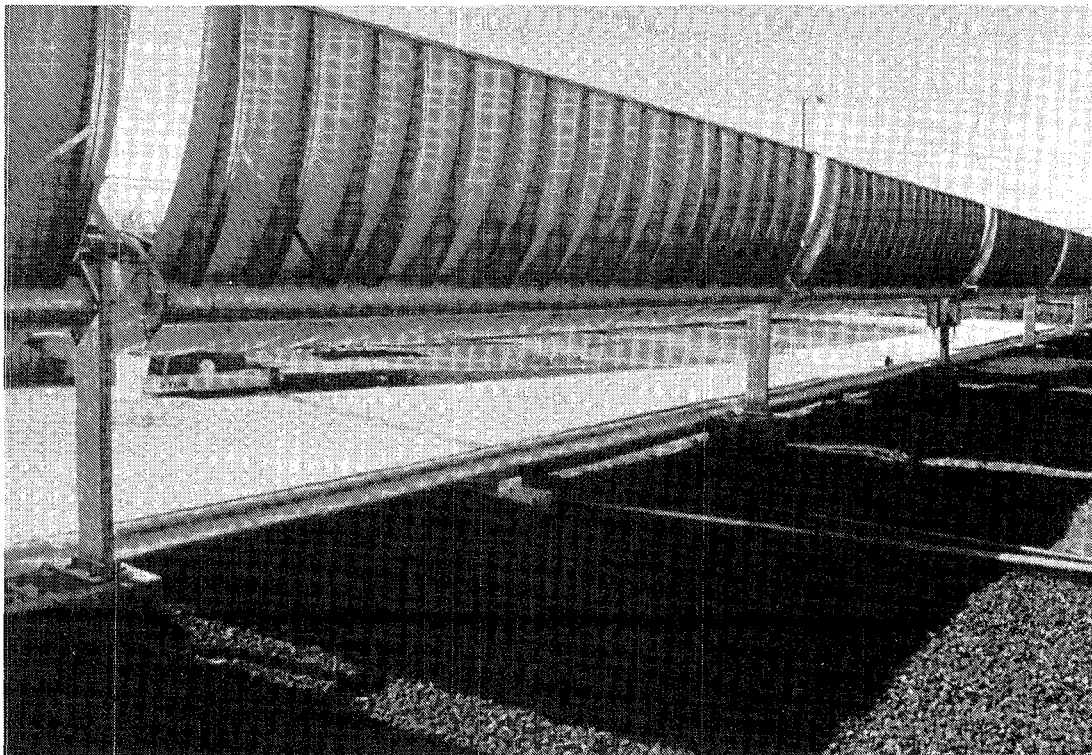
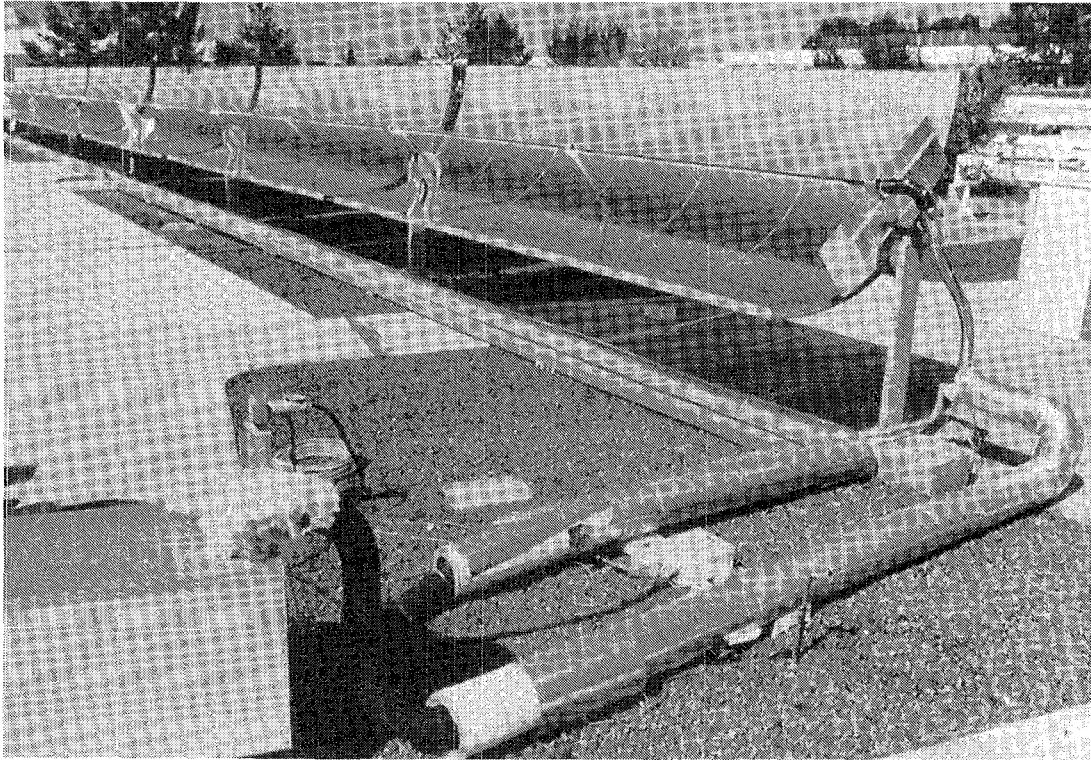


Figure 4-3. Acurex PRDA Collector Drive String with Glass/Steel Laminated Reflector Panels (Above - front view; Below - rear view)

b. Solar Kinetics Collector. The collector design by Solar Kinetics is a spot-welded assembly of sheet steel faces, ribs, and stringers that form an 8-by-20-ft rigid trough structure. All spot welding is done with the front face held on an accurate male mold. Testing of the trough structure has verified its wind, gravity, snow, and torsional load capabilities. The front face is covered with FEK-244 reflective film for the initial units; a glass/steel laminate under development at Solar Kinetics may be used in subsequent units.

At the end of FY 1982, two collector modules had been mounted on (and later removed from) pylons with a drive system for fit as well as for drive and tracking operational checks. Most of the parts and components for a complete 120-ft drive string and fluid test loop had been fabricated or obtained by Solar Kinetics, but system assembly, operational checkout, and performance testing are yet to be accomplished. All major components (trough, drive, tracker, pylons, etc.) have been subjected to extensive life-cycle and/or load testing for design verification.

c. Suntec Collector. The Suntec, Inc., collector design (Figure 4-4) incorporates a large torque tube plus a framework of ribs and stringers fabricated from sheet steel stock. Glass mirror panels, thermally sagged to parabolic contour prior to silvering, are installed on the framework. Two glass panels are required between vertex and rim. Suntec performs the glass sagging and contracts the silvering. A rubber protective coating is applied over silver/copper/paint layers, and each 0.825 by 0.984 m (32.5 by 38.75 in.) mirror is attached to the structure with four bolts through holes in the mirror cushioned by rubber grommets.

The individual collector module is 3.05 by 5.94 m (10 by 19.5 ft), with six modules forming a drive string. An 18.3 m (60 ft) half drive string was connected to a test loop in early summer 1982 for performance testing with water as the heat transfer fluid and operation at temperatures from 121 to 204°C (250 to 400°F). Preliminary efficiencies were in the mid 60's at 204°C (400°F) output. Changing to an oil heat transfer fluid was accomplished in late summer; however, instrumentation failures have delayed additional testing at higher temperatures. Issuance of a final report is pending test completion.

d. Winsmith Speed Reducer Development. The Winsmith Company designed and fabricated prototype gearboxes for parabolic trough collector drive systems. These two-stage gearboxes, having a planetary first stage and a worm second stage, were tested at Winsmith and SNLA (Figure 4-5). The worm secondary helps provide a locking feature to prevent reverse drive due to wind or other loads. Based upon prototype testing, modifications were made in the design, after which three units representative of regular production were fabricated and tested. Efficiencies of up to 34% were obtained. The final report will be issued during FY 1983 after data become available from extended life test of one unit at Winsmith.

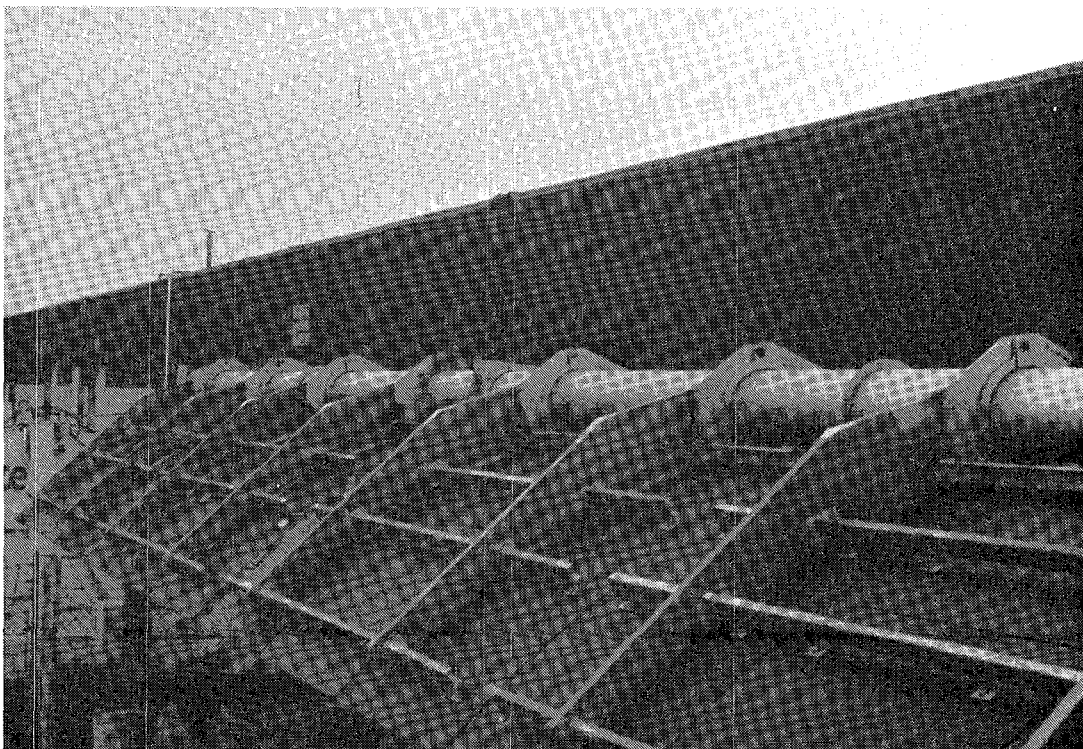
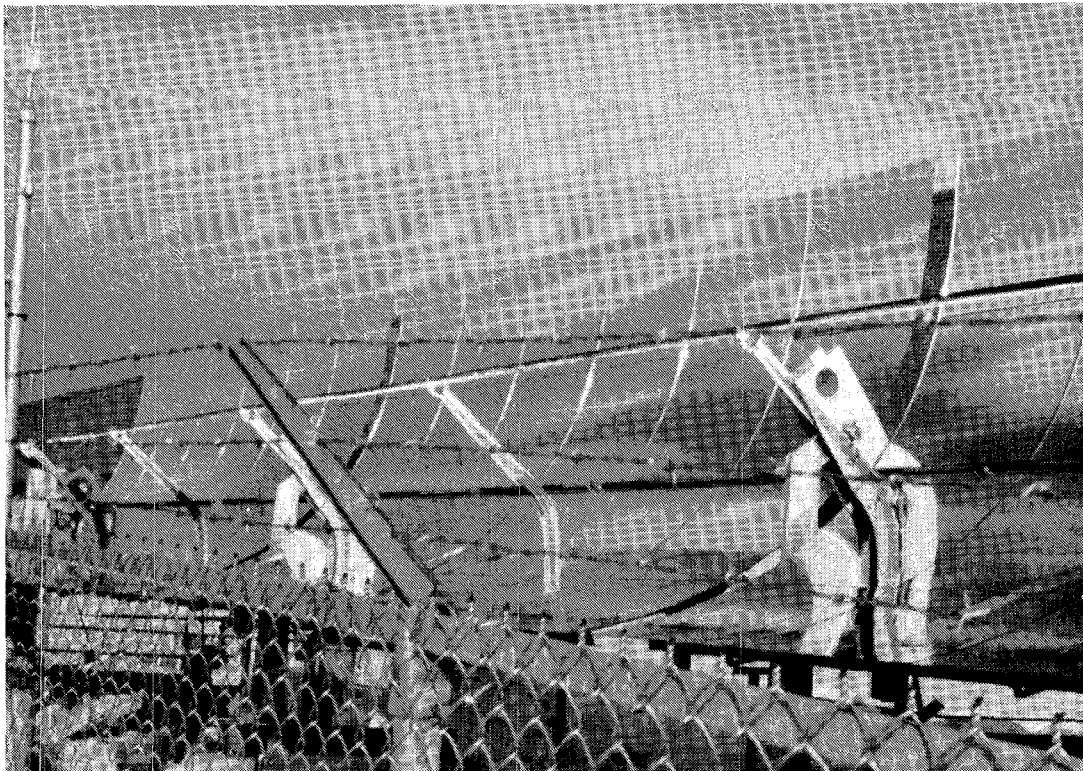


Figure 4-4. Suntec PRDA Collector with Formed Glass Mirrors  
(Above - front view; Below - rear view)



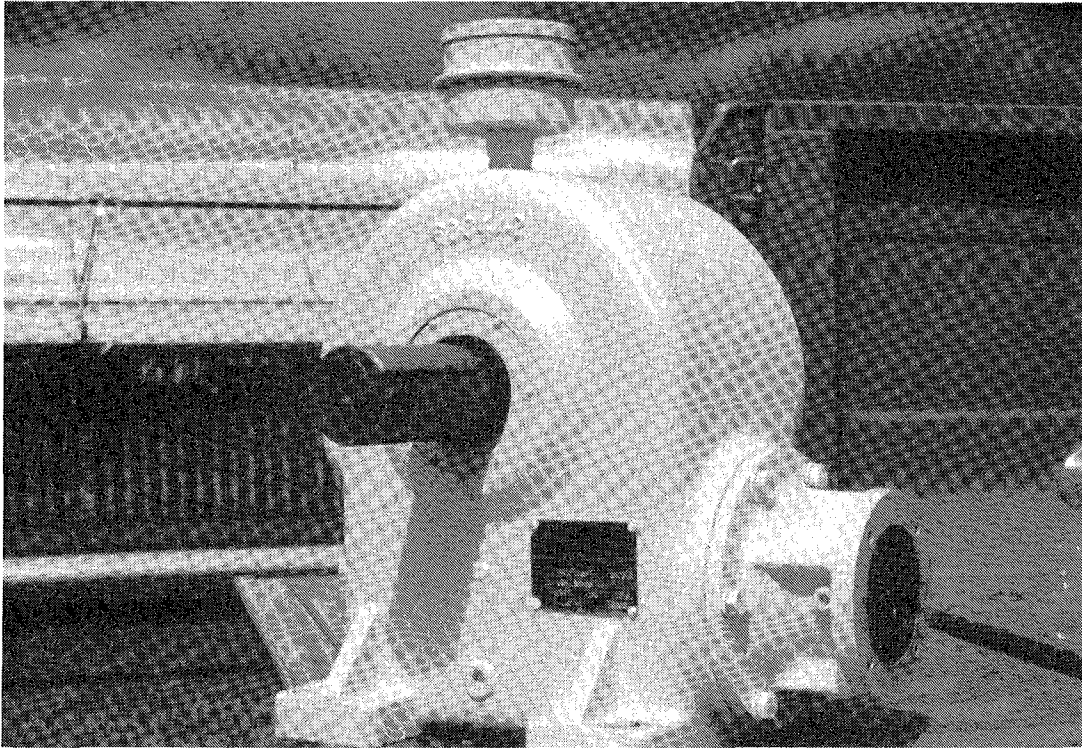


Figure 4-5. Winsmith Two-Stage Speed Reducer for Collector Drive Systems

## B. SYSTEMS EXPERIMENTS AND ANALYSES

### 1. 150-kWe Solar Irrigation Project

The 150-kWe Solar Irrigation Project (Figure 4-6) is a parabolic trough system that supplies electrical energy from a 150-kW turbine/generator to the local electrical cooperative, Electrical District 2, at Coolidge, Arizona. The power is fed to the utility grid in exchange for power to run three 50-hp irrigation pumps located on the Dalton Cole Farm.

At the time of its dedication in November 1979, the facility was the world's largest operating solar thermal power plant. The site, halfway between Phoenix and Tucson, was selected in February 1977. Acurex Corporation was the prime contractor for the project and supplied the solar collectors. The major subcontractors were Sundstand Corporation, supplier of the organic Rankine-cycle power generation unit, and Sullivan and Masson Consulting Engineers, who with Acurex developed the detailed design.

The collector field is made up of 2140 m<sup>2</sup> (23,040 ft<sup>2</sup>) of Acurex line-focus parabolic trough collectors arranged in eight  $\Delta T$  loops with a north/south orientation. Coilzak, an anodized polished aluminum with a reflectivity of 70%, was originally used for the reflective surface of the collectors. The average performance of this subsystem was increased to more than 80% by replacement of the Coilzak with FEK-244.

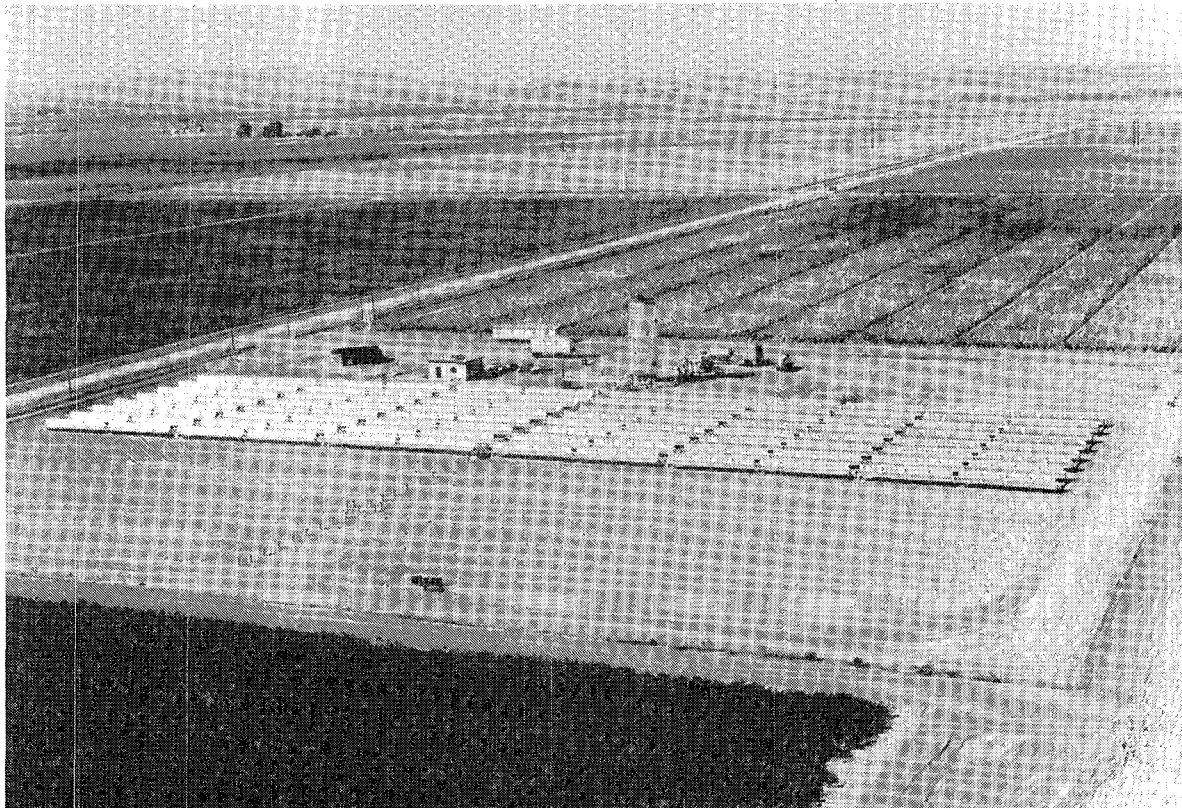


Figure 4-6. The 150-kWe Solar Irrigation Project in Operation Among the Cotton Fields of the Gila River Valley in Coolidge in Southern Arizona

Solar energy is converted to electrical energy by means of an organic Rankine-cycle power conversion module that uses toluene as the working fluid. The unit is complete with gear reduction and a 440-Vac, 3-phase, 60-Hz, high-efficiency generator. Supporting equipment includes a vapor condenser for condensing the toluene and a vaporizer assembly consisting of a preheater, an evaporator, and a superheater for vaporizing the toluene. Energy is stored in a  $110\text{-m}^3$  (30,000-gal) insulated tank 4 m (14 ft) in diameter and 15 m (50 ft) high. The control subsystem monitors and controls the collection and storage of solar energy and the generation and supply of electrical power. In addition, the subsystem helps prevent system-related anomalies such as high temperatures in the collector field and takes preventive action in case of natural events such as gusty winds. A system schematic is shown in Figure 4-7. The system operated reliably in an automatic mode. The performance was somewhat lower than design because the collector field is one-half the design size.

DOE participation in the project was completed in 1982. The system ownership was transferred to the host, Dalton Cole, who is continuing to operate the system for farm irrigation.

## 2. Modular Industrial Solar Retrofit Project

The Modular Industrial Solar Retrofit (MISR) Project is a DOE effort to bring together the technology developed for parabolic trough solar

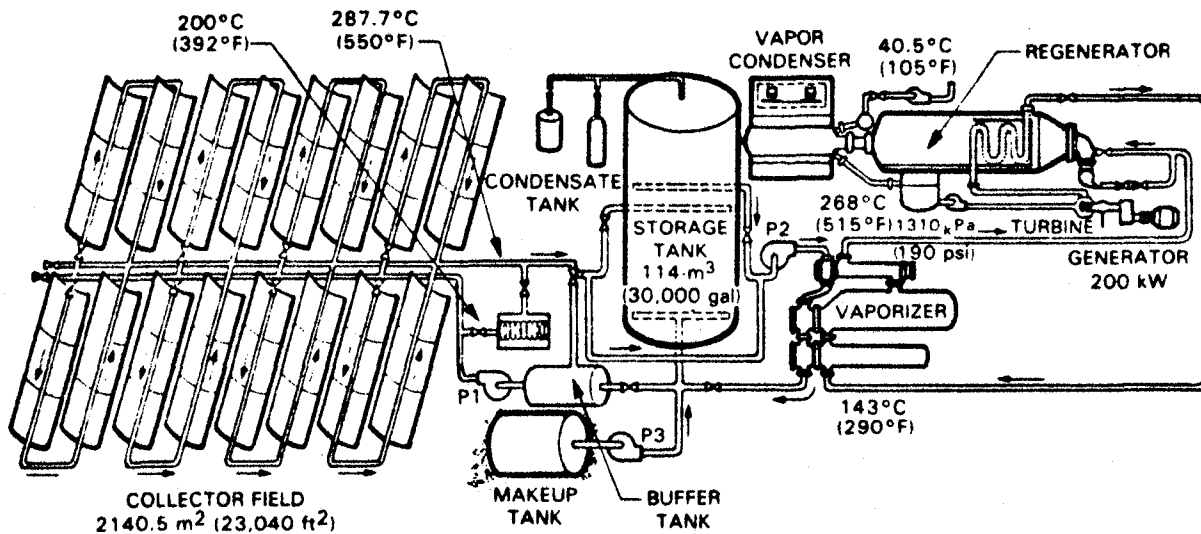


Figure 4-7. 150-kWe Solar-Powered Irrigation Facility Flow Diagram

systems and to assist solar system suppliers to incorporate this integrated technology into modular system designs.<sup>2</sup> The project goals are to determine one-of-a-kind system costs and identify one-of-a-kind design problems by developing and testing a modular (packaged) unit that would have broad industrial process heat applications. The first unit will be purchased by DOE for design evaluation purposes and to remove the one-of-a-kind design problems. Sandia National Laboratories-Albuquerque is responsible for MISR project management.

SNLA, working with Stearns-Rogers Services, Inc., developed the design requirements and a sample system design.<sup>3,4</sup> The selected system size of 2300 m<sup>2</sup> is based on an industrial process heat user survey of five southwestern states and a study of project cost versus system size. An artist's

<sup>2</sup>Alvis, R. L., "Modular Industrial Solar Retrofit Project (MISR)," Solar Industrial Process Heat Pre-Conference Proceedings, SERI/CP-632-951, December 16-19, 1980, pp 105-110.

<sup>3</sup>Wally, K., Modular Industrial Solar Retrofit System Constraints, Specifications, and Guidelines, SAND81-1300, Sandia National Laboratories, Albuquerque, New Mexico, August 1981.

<sup>4</sup>Alvis, R. L., Safety Analysis Report, MISR Qualification Test System and Test Site, SAND82-1159, Sandia National Laboratories, Albuquerque, New Mexico, September 1982.

concept of a MISR system is shown in Figure 4-8, and a system description is shown in Figure 4-9. A summary of MISR system design requirements is listed below:

- (1) The designs are for ground mounting only.
- (2) System design life is 15 years.
- (3) The system will automatically acquire and track the sun in either clear or partially clouded skies.
- (4) The system will produce saturated steam at any pressure up to 1.73 MPa (250 psi).

Late in FY 1981, SNLA awarded five contracts to industry for MISR system design, fabrication, and installation of qualification test systems (QTS). The companies receiving contracts, along with some of the system design characteristics, are shown in Table 4-4.

During FY 1982, test facilities were designed and constructed at the Solar Energy Research Institute (SERI) in Golden, Colorado, and at SNLA in Albuquerque, New Mexico. The qualification consisted of testing one QTS of each design, with the respective test facility supplying the necessary support equipment. This equipment includes a propane field heater to represent the balance of the design's collector field, heat dissipation, feed water, and

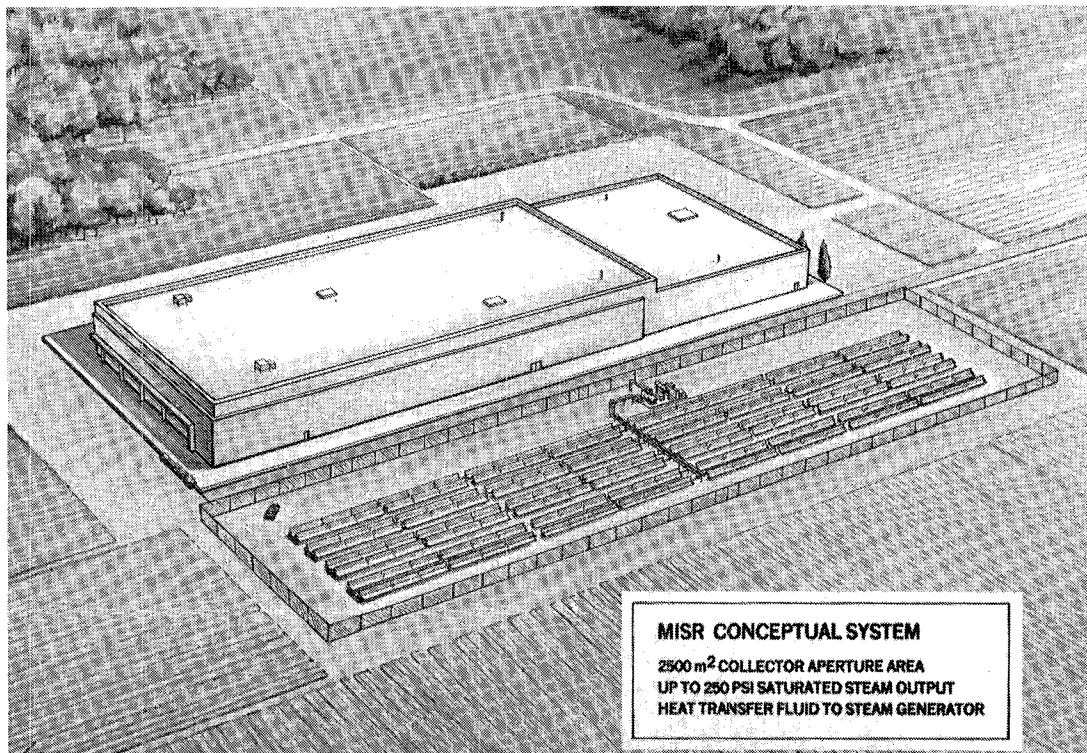


Figure 4-8. Rendering of a 2300-m<sup>2</sup> MISR System Located Near a Factory Using Process Steam



Table 4-4. MISR System Design Characteristics

System Designer	Collector Manufacturer	Collector Reflector Type	Heat Transfer Fluid	Collector Field Size, m <sup>2</sup>
Acurex Corp. 485 Clyde Ave. Mountain View, CA 94042	Acurex T-3001	Thin glass/sheet metal laminate	Oil type	2497
BDM Corp. 1801 Randolph Rd., SE Albuquerque, NM 87106	Solar Kinetics T-700	3M FEK (aluminized acrylic)	Oil type	2341
Custom Engineering, Inc. 2805 South Tejon St. Englewood, CO 80110	Custom Engineering/ Budd	Thin glass	Oil type	2303
Foster Wheeler Solar Development Corp. 12 Peach Tree Hill Rd. Livingston, NJ 07039	Suntec	Sagged glass	Water	2586
Solar Kinetics, Inc. 3300 Century Circle Irving, TX 75060	Solar Kinetics T-800	3M FEK or YS94 or glass	Oil type	2498

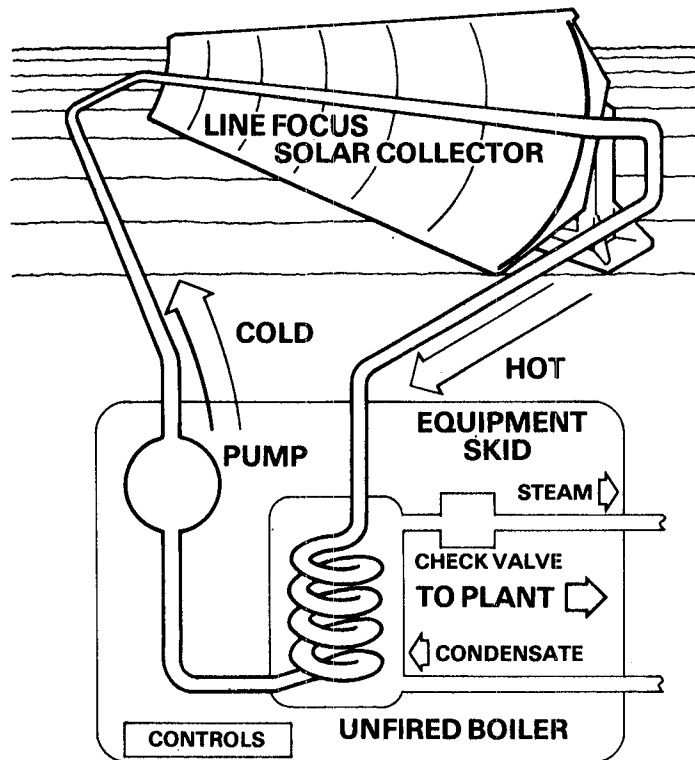


Figure 4-9. Typical MISR Steam System

data acquisition. The SERI test site is shown in Figure 4-10, and the SNLA site in Figure 4-11. The Acurex, BDM, and Foster-Wheeler qualification test systems were installed and testing initiated during FY 1982. Systems by Custom Engineering and Solar Kinetics were partially installed by the end of FY 1982. Although the evaluation has not been completed, many one-of-a-kind design and component problems (most of which are related to state-of-the-art equipment) have been discovered and corrected. Finding and correcting these problems are goals of the MISR project. In FY 1983, all remaining problems should be found and corrected, and the evaluation of designs completed. To date, the systems have proved to be superior to past system designs.

Another part of the MISR project is the interface design development required to place a MISR system into operation at a specific industrial plant. In FY 1982, DOE ALO solicited companies to participate in this activity, and ten plant sites were competitively selected. The MISR system suppliers were assigned two sites each under a contractual arrangement to develop the interface designs using their MISR system. The participating companies are listed in Table 4-5. Eight of the ten designs were completed in FY 1982. The remaining two will be completed in FY 1983, and the information disseminated at a conference scheduled for March 1983.

### 3. Small Solar Power Systems Project

The Small Solar Power System (SSPS) Project is a cooperative effort of nine International Energy Agency (IEA) countries to design,

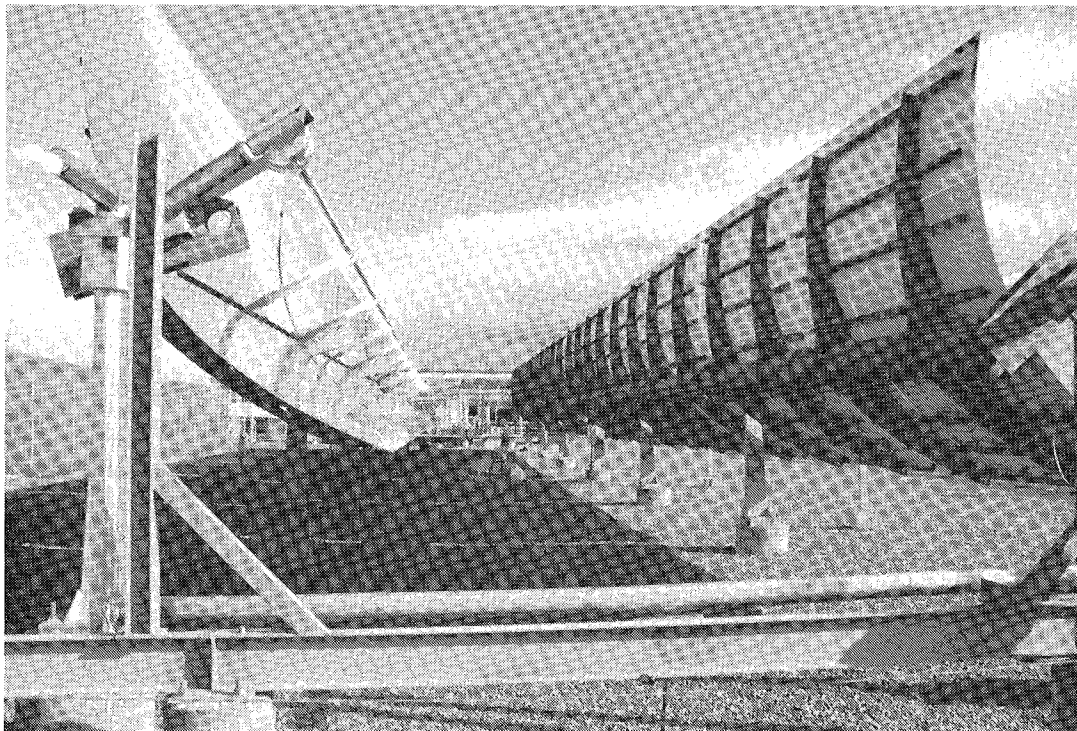


Figure 4-10. The Foster Wheeler/Suntec MISR System Under Test at the SERI Qualification Test Facility



Figure 4-11. MISR Qualification Test Facility at SNLA

Table 4-5. MISR Interface Design Development Contracted Companies

MISR Designer	Interface Plant
Acurex Corporation	Formica Corp., Sunset/ Whitney Ranch, California
	Lange & Gangnes Corp. White City, Oregon
BDM, Inc.	A. E. Staley Mfg. Co. Monte Vista, Colorado
	Prepared Foods, Inc. Santa Teresa, New Mexico
Custom Engineering, Inc.	Cyprus Industrial Minerals Co. Three Forks, Montana
	Wayne Poultry Pendergrass, Georgia
Foster-Wheeler Development Corporation	Davis & Geck Manati, Puerto Rico
	Western Electric Norcross, Georgia
Solar Kinetics, Inc.	El Paso Products Co. Odessa, Texas
	Pabco Insulation Division Fruita, Colorado

construct, test, operate, and evaluate two different types of solar thermal electric plants utilizing the organizational structure of the IEA. The nine countries are Austria, Belgium, Greece, Italy, Spain, Sweden, Switzerland, United States, and West Germany. A central receiver solar power plant (see Section II.B.2) and a distributed collector power plant were designed and constructed near Almeria, Spain. The project emphasizes use of available technology, minimizing research and development, and provides for flexibility of design and operation. The distributed system portion is shown in Figure 4-12. (Refer to Figure 2-18 for an aerial view of the two-system plant.) The operating agent for the project is the German Aerospace Laboratory, DFVLR.

The distributed collector system (DCS) design and construction contract was awarded to Acurex Corporation of the United States. Much of the contribution from the nine participating countries was in the form of hardware, which

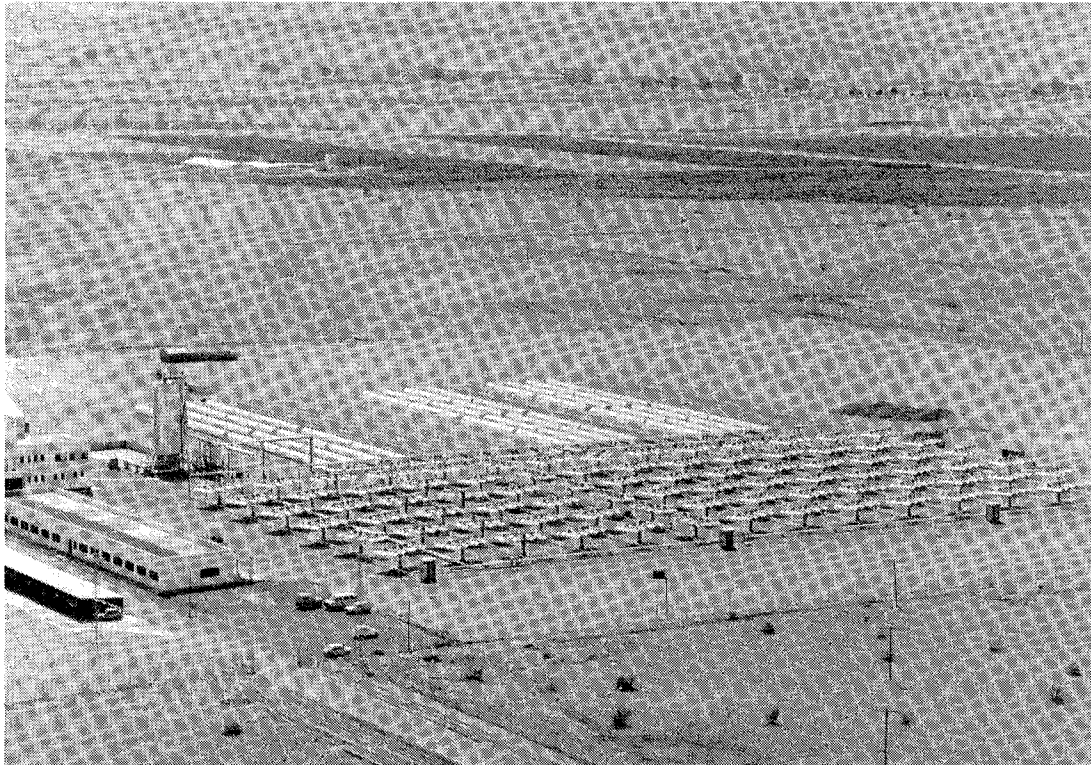


Figure 4-12. Distributed Collector System of the SSPS Project

Acurex incorporated into the system design. For instance, the system uses two types of line-focus collectors: 2688 m<sup>2</sup> of two-axis tracking collectors manufactured by M.A.N. of West Germany and 2674 m<sup>2</sup> of single-axis tracking parabolic collectors manufactured by Acurex.

Construction, which began in December 1979, was completed on schedule in August 1981, with only a small increase in cost. The plant became operational in late summer 1981, and the formal dedication took place on September 21, 1981. FY 1982 activities included acceptance testing and initiation of the operational phase, which is now continuing routinely. A reduction in field size due to funding limitations and lower than average insolation have resulted in reduced operational flexibility. The system seldom operates at rated capacity (500 kWe at 920 W/m<sup>2</sup>) except from thermal storage. The power conversion equipment is started when the storage system is approximately one-half charged and is allowed to run until storage is depleted while the field is continuing to add energy.

Several problems and failures with the non-solar equipment (pumps, valves, heat exchangers, etc.) have delayed completion of a comprehensive performance evaluation. In April 1982, a lightning strike a few kilometers away on the power grid caused severe damage to two of the three grid/site interconnecting transformers. Improper connection of the lightning protection equipment resulted in greater than predicted damage. These problems, coupled with less than 1500 hours of insolation above 500 W/m<sup>2</sup> during 1982, have severely limited operating time.

Since January 1982, operation of the plant has been under contract to Sevillana, the local utility. Operation has been two-shift, seven days a week, since February 1982. The maintenance crew is one-shift, five days per week during daylight hours. Any maintenance outside of this standard shift requires prior arrangement and overtime pay. From its dedication (September 21, 1981) until June 15, 1982, the plant has produced electricity approximately 35% of the operating time and has collected energy over about 52% of that time. It has not operated approximately 14% of this period. Operating times for the three main subsystems during this period are listed below:

- (1) M.A.N. collectors: 846 hours
- (2) Acurex collectors: 618 hours
- (3) Power conversion system: 333 hours

The difference in operating times resulted from a "shutdown for safety" caused by inoperation of the Acurex "uninterruptable power supply" from February 26 to March 30. Both collector fields were out of service from May 3 to 21 because of lightning damage. Monthly field efficiency has ranged from 39 to 45% for Acurex and 22 to 47% for the M.A.N. field. Measured peak performance figures are shown in Table 4-6.

An important observation made during operation is that atmospheric pollution at the site has been greater than expected. The glass/silver mirrors used on the solar collectors lose between 0.2 and 0.6% reflectivity per day. A study is being conducted to find ways of alleviating this effect on both system performance and associated cleaning costs.

Insights and observations from SSPS operation thus far are summarized below:

- (1) The solar specific equipment has performed close to expectations, with the collector fields being within 3% of that proposed for the environmental conditions.
- (2) Maintenance and repair problems with non-solar equipment have been higher than expected.
- (3) Mirror soiling rate is higher than expected.
- (4) Plant design power can be obtained only by operating from thermal storage.

Continued operation is expected to uncover any further problems and allow correction of all commercial equipment. Additional trough collectors, which will increase the operating time and performance of the system, are to be installed in FY 1983 by Italy.

Table 4-6. Peak Performance Measurements

Initially Expected Peak Performance		Measured Peak Performance	
DCS Plant (Design Point)		1981	1982
Field Efficiencies, %			
Acurex	55.4	54.6	55.5
M.A.N.	50.1	46.0	44.1
Total Field	52.8	50.7	50.3
Power Conversion System	22.4	19.6	19.2
Total Plant	10.1	11.5	10.9
Maximum Electrical Power, kWe	577	600	600
Parasitic Power, kWe	70	58.8	58
Minimum NIP for Start-Up, $W/m^2$	300	--	500
Electrical Power Generation, MWe-h/yr	750	--	120

### C. INDUSTRIAL PROCESS HEAT PROJECTS

The Industrial Process Heat (IPH) Program was initiated by DOE in 1976 to evaluate the technical feasibility of solar thermal energy for industrial process heat applications. Since then, there have been 17 solar energy systems installed in four phases at industrial plants throughout the country. The systems have used a variety of collectors including flat plates, evacuated tubes, and parabolic troughs. A number of the earlier experiments have been transferred to their respective hosts, others have been upgraded or are in the process of upgrade, and two have been terminated. Construction of seven trough experiments, which are still receiving funding from DOE, was completed by FY 1982 or during FY 1982. At the end of the fiscal year, all of these systems were operating. These active projects, their locations, and prime contractors are listed in Table 4-7.

The seven active IPH systems are installed at industrial sites where the energy produced is supplied directly to the plant's energy distribution line. The systems, which are instrumented for detailed data collection, are being

Table 4-7. IPH Projects: Locations and Prime Contractors

Project	Location	Contractor
Home Laundry Company	Pasadena, California	Jacobs Engineering Company
Southern Union Refining Company	Lovington, New Mexico	Energetics Corp.
Lone Star Brewery	San Antonio, Texas	Southwest Research Institute
Ore-Ida Foods	Ontario, Oregon	TRW
Dow Chemical Company	Dalton, Georgia	Foster-Wheeler Development Corp.
USS Chemical Company	Haverhill, Ohio	Columbia Gas
Caterpillar Tractor Company	San Leandro, California	Southwest Research Institute

operated under the DOE Solar Thermal Technology Program to obtain experimental data on performance, reliability, and operation and maintenance (O&M) costs. After the operational period, the systems will be transferred to the industrial hosts for continued operation. The systems are planned as continuing sources of energy for the industrial plants and will serve as examples of solar energy applications for other prospective users.

In FY 1982, difficulties were encountered with solar collectors, steam production equipment (pumps, valves, and piping), and data acquisition systems; however, by the end of the year five of the seven experiments were operating routinely; Caterpillar Tractor was awaiting repairs to the collectors; and Ore-Ida Foods required repair of the main circulating pump.

Following is a description of each of the experiments and a brief account of their accomplishments.

#### 1. Home Laundry

The Home Laundry Company Project in Pasadena, California, employs 604 m<sup>2</sup> of Del-Jacobs parabolic trough collectors that supply energy to a tube-in-shell steam generator to produce 760 kPa (110 psi) steam. The system also can be operated in an optional mode to produce 71°C (160°F) domestic hot water. The collectors are located on the roof of a special



structural-steel platform attached to the laundry. The project was designed, constructed, and is currently operated by Jacobs Engineering Company. The laundry handles both laundry and dry cleaning and has process heat requirements for hot water, super-heated hot water, and steam.

Construction of the project was nearing completion at the beginning of FY 1982. Acceptance tests were conducted during the week of April 2, 1982, and the operational period (Phase III) began in September after problems disclosed during acceptance testing were corrected. From April through September, the system was operated to provide hot water for the laundry although comprehensive operational data were not obtained because of data acquisition problems. To provide a full year of operation, the Phase III contract end date was extended from April 1983 to September 1983.

## 2. Southern Union Refining Company

The project at Southern Union Refining Company, Lovington, New Mexico, uses 937 m<sup>2</sup> of Solar Kinetics T-700 collectors located in a field near the refinery (Figure 4-13). It was designed and built through the combined efforts of Energetics Corporation (formerly Monument Solar Corporation), Bridgers and Paxton Consulting Engineers, and the New Mexico Solar Energy Institute. Energetics Corporation is currently operating the



Figure 4-13. Trough IPH Experiment at Southern Union Refining, Lovington, New Mexico

project. Design of the system, which provides steam to the refinery at 191°C (375°F), began in September 1978, with operation beginning in January 1982.

The Southern Union project operated and produced data for seven months during FY 1982. During the seven months, the system operated at a thermal efficiency of 18% to produce 157 GJ (148 MBtu) for the refinery at a measured insolation of 867 GJ (821 MBtu) in the plane of the collector field.

An equipment upgrade is planned to retrofit the receiver tubes and correct hydraulic and control system problems.

### 3. Lone Star Brewery

The Lone Star Brewery, located in San Antonio, Texas, has 878 m<sup>2</sup> of Solar Kinetics collectors. The system produces steam to augment the brewery process heat supply. The steam is used in all processes of brewing beer, including washing, canning, pasteurizing, and cleaning. It was designed, built, and is being operated by the Southwest Research Institute. Design began in 1978, construction was completed in December 1981, and the system was accepted in January 1982. The first operational data were recorded in December, and monthly performance and O&M data have been produced each month since then.

During the year, the contractor and the Solar Energy Research Institute (SERI) developed two new predictive models based upon improved weather data and actual performance. The new models predicted a theoretical performance of about 40% of the originally predicted performance. Actual performance was low because of excessive down time.

During FY 1982, the total energy delivered by the solar IPH system at a thermal efficiency of 25% was 340 GJ (323 MBtu); insolation measured in the plane of the collector was 1368 GJ (1296 MBtu).

A retrofit of receiver tubes is planned for the Lone Star Brewery system to correct oil leakage and glass breakage. Problems with hydraulic drives and controls also will be corrected.

### 4. Ore-Ida Foods

The Ore-Ida project was built in Ontario, Oregon, by TRW, the prime contractor. It employs 884 m<sup>2</sup> of Suntec collectors and uses pressurized water as the heat transfer fluid. Steam, generated in a flash tank at 2070 kPa (300 psi), is used to heat cooking oil for frying potatoes. Water, rather than oil, is used as the collector fluid to avoid the possibility of contaminating the cooking oil.

The design phase began in July 1979, and construction was completed in June 1981. Due to recurring failure of the main pump, few data were collected in FY 1982, and O&M data were not reported.

Plans for FY 1983 include (1) modifying the system to correct equipment problems and to reduce thermal loss and (2) procuring spare parts to avoid shutdown when malfunctions occur. The experiment will be continued through direct operation by Ore-Ida Foods.

5. Dow Chemical Company

The Dow Chemical Company solar IPH system is located in Dalton, Georgia. It employs 923 m<sup>2</sup> of Suntec collectors mounted on a 10 degree south-facing slope and provides steam to the styrene butadiene rubber latex plant at Dow. The system produces 1030 kPa (150 psi) saturated steam in an unfired steam generator, using Dowtherm as a heat transfer fluid.

The design contract for the plant was awarded to Foster-Wheeler Development Corporation in 1978. An acceptance test was performed upon completion of construction in November 1981 by Foster-Wheeler, who is also conducting the operational phase. The project operated much of the fiscal year; however, a number of problems with the data acquisition system resulted in generation of incomplete data on performance and O&M.

6. USS Chemical Company

The IPH system at the United States Steel (USS) Chemical Company in Haverhill, Ohio, (Figure 4-14) is one of two projects using large collector

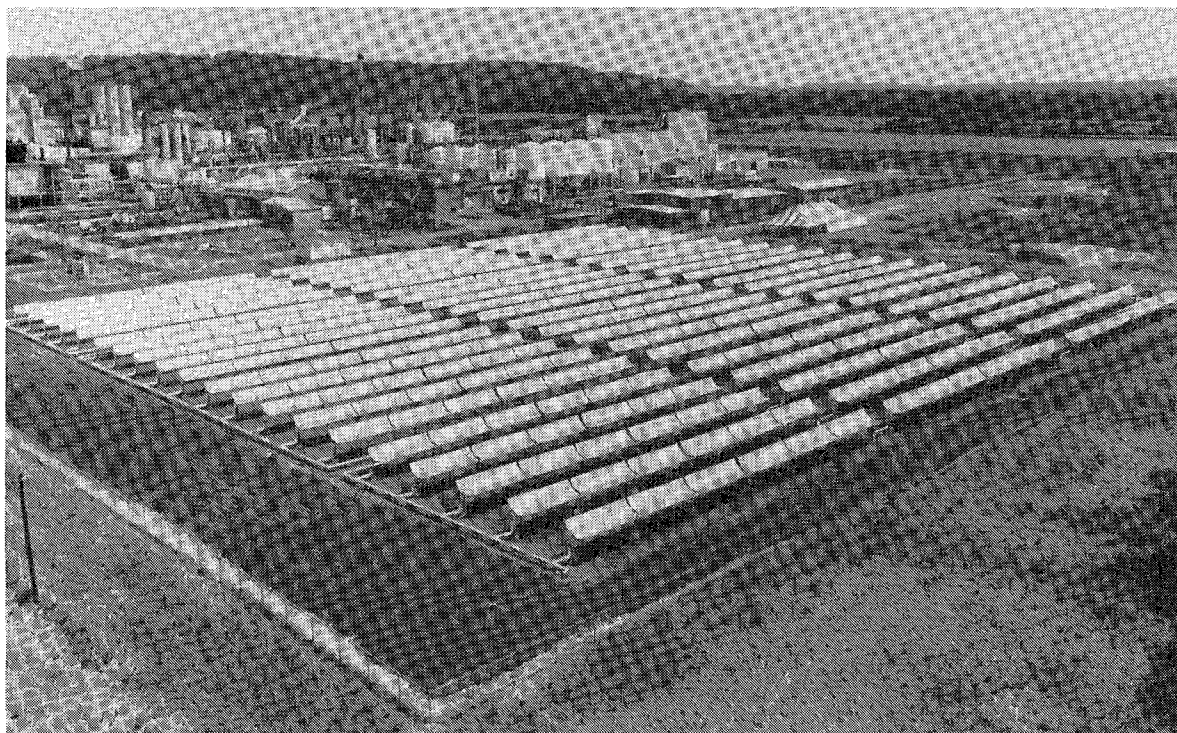


Figure 4-14. Trough IPH Experiment at the USS Chemical Company, Haverhill, Ohio

arrays (4683 m<sup>2</sup> or 50,000 ft<sup>2</sup> aperture area) and advanced Solar Kinetics T-700 collectors. The collectors operate at 218°C (425°F) with Therminol as the heat transfer fluid to generate steam in an unfired boiler. The steam is used in the production of polystyrene. Columbia Gas System Service Corporation (Columbia Gas) designed and built the solar energy system.

The design phase began in September 1979, construction was completed in March 1982, and acceptance testing took place in May 1982. At the beginning of the calendar year, a major redirection of solar energy use occurred when it was determined that 1040 kPa (150 psi) steam was no longer required by the plant. As the fiscal year closed, steam at 360 kPa (52 psi) was being produced by the system, which was sized to provide steam at 1.25 kg/sec (10,000 lb/h) out of a total plant demand of 20 kg/sec (160,000 lb/h).

Problems with the collectors, such as glass breakage on receiver tubes, oil leakage at the receiver joints, hydraulic drive problems, pylon/collector interference, and speckling of the receiver tubes, were identified; solutions developed; and improvements initiated by the end of the fiscal year. Despite the problems, the system operated from July through September 1982. During September, the system operated 20 of 30 days and produced 103,700 kg (228,000 lb) of steam.

## 7. Caterpillar Tractor Company

Caterpillar Tractor Company is hosting the second solar IPH project using a large collector array. The solar energy system consists of 4682 m<sup>2</sup> (50,000 ft<sup>2</sup>) of Solar Kinetics T-700 collectors mounted on the roof of the Caterpillar Tractor plant in San Leandro, California (Figure 4-15). The system, built by Southwest Research Institute, produces hot water for washing machined parts and is expected to produce 12,600 GJ/yr (12,000 MBtu/yr), constituting 1.3% of the total plant demand. The system is open loop, with solar-heated water entering the main water heating system of the plant through a hot water process line and returning through a hot water header. Construction was completed in May 1982; however, acceptance testing is being delayed until early FY 1983 pending a retrofit to prevent the collectors from striking the pylons. The system operated the last 2-1/2 months of FY 1982, and instantaneous measurements of total radiation, flow rates, and temperature differences were used to provide a preliminary assessment of system performance.

Future plans include completion of acceptance testing and continuation of the experiment through September 1984 under the existing cooperative agreement.

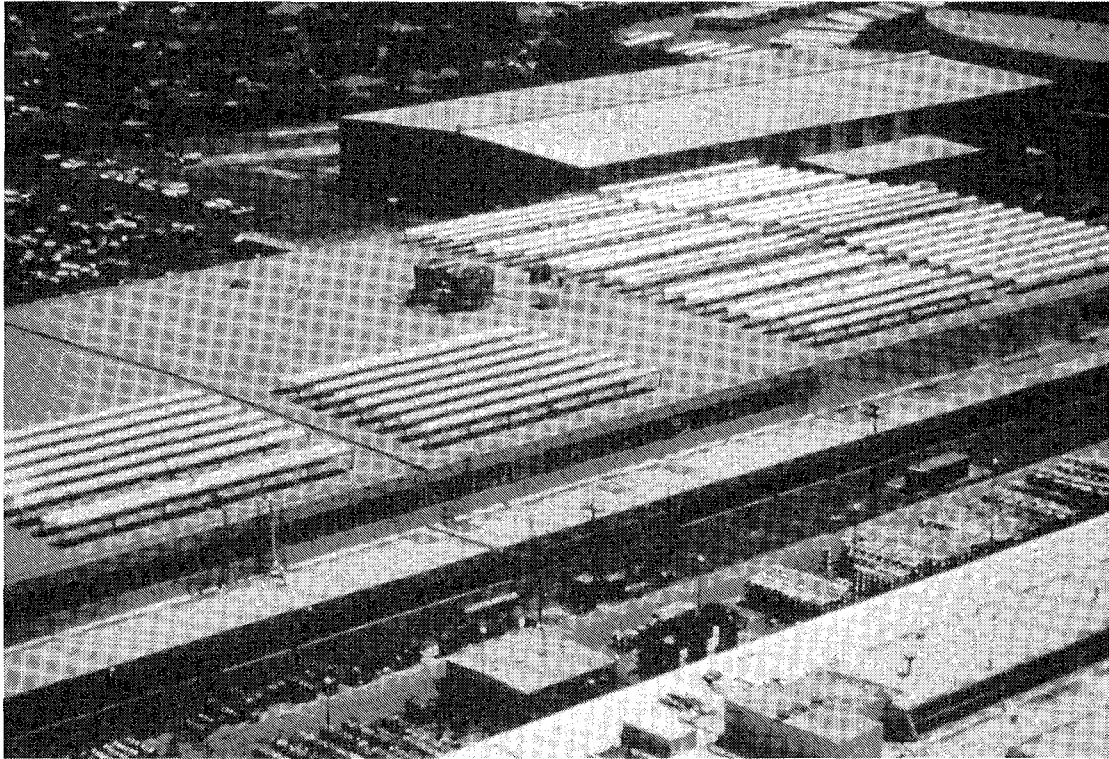


Figure 4-15. Trough IPH Experiment at the Caterpillar Tractor Company, San Leandro, California

## SECTION V

### OTHER TECHNOLOGIES

In addition to the three solar thermal core technologies (central receiver, parabolic dish, and parabolic trough), three additional technologies (hemispherical bowl, salt-gradient solar pond, and agricultural applications) being developed by the Solar Thermal Technology Program made substantial progress during FY 1982. Previous cost estimates for a 5-MWe hemispherical bowl power plant were verified by an independent consulting firm. Several salt-gradient solar pond research projects are underway, feasibility studies for solar pond power plants at Truscott Brine Lake and the Great Salt Lake were completed, and site specific-studies for a solar pond at the Salton Sea were carried out. Also, a number of agricultural applications were demonstrated, including greenhouse heating, crop drying, food processing, and heating for livestock shelters.

#### A. HEMISPHERICAL BOWL TECHNOLOGY

The hemispherical bowl solar collector is designed to take advantage of a unique optical characteristic of a concave spherical surface. Such a surface, when illuminated, reflects light onto a line that is aligned with the sun. This optical characteristic holds true, regardless of the angle of the sun relative to the bowl even if part of the surface is in shadow at low sun angles. This phenomenon makes possible a simple solar collector concept in which the concentrator can be fixed (and therefore large) and the receiver swivels about a point at the center of curvature to track the reflected focal line throughout the day. The bowl concept is being evaluated for DOE at a facility near Crosbyton, Texas (Figure 5-1). The Crosbyton bowl, designed and built by a team of researchers from Texas Technical University, and E-Systems, Inc., entered its third year of testing in FY 1982.

The Crosbyton bowl, which is referred to as the Analog Design Verification System (ADVS), has an aperture of 20 m and is constructed of a mosaic of silvered glass facets, each about 1 m across. The mirrors are stressed to a spherical shape and bonded to paper honeycomb backing structures. The facets are fastened to curved tubular stringers. The receiver consists of a 15-cm pipe around which tubing is wrapped. Treated water is pumped through the tubing where it is heated and boiled to nominal outlet conditions of 540°C and 6.8 MPa, similar to those of a conventional power plant. Outlet temperatures and pressures of about 720°C and 8.8 MPa, respectively, have been experienced without incident. The receiver is counterweighted and driven in two axes by electric motors to remain in line with the sun (Figure 5-2).

The fixed concentrator of the hemispherical bowl embodies both the strength and the weakness of the concept. Because the concentrator is fixed, a cosine loss penalty in two axes is inherent, which results in a lower theoretical annual energy collection capability per unit of aperture area than either the central receiver or the parabolic dish. To compensate for this disadvantage, the bowl must be less expensive to install and operate than





Figure 5-1. The 20-m Hemispherical Bowl in Operation near Crosbyton, Texas. The building to the right and the pad behind it contain water treatment, heat rejection, and mechanical equipment. The control room and offices are in the larger building.

competing technologies. Because the fixed concentrator can be deployed in large modular sizes (about 2800 m<sup>2</sup> rated at 500 kWe peak), it can provide substantial economy-of-scale benefits.

Because economic competition is a key issue regarding the bowl concept, emphasis has been placed on cost reduction techniques and on accurate cost estimates of construction and installation. In FY 1981, the project team of Texas Tech, E-Systems, and Foster-Wheeler prepared a cost estimate for a 5-MWe hemispherical bowl plant. This plant would consist of ten 60-m bowls and conventional steam power balance-of-plant equipment. The plant was assumed to be a self-contained, hybrid system that would be capable of producing electricity from solar steam or from steam generated in a fossil fuel fired boiler. The plant, therefore, would be able to produce power whether or not the sun is shining. The estimated cost of such a system is \$28.3 million in 1981 dollars.

To provide DOE with an independent cost estimate for comparison purposes, a contract was awarded by SNLA to A. T. Kearney of Chicago, a consulting firm with experience in cost estimating. The Kearney estimate for the same plant and the same assumptions was \$31.4 million; a reasonably good correlation.<sup>5</sup>

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<sup>5</sup>Kearney Management Consultants, Hemispherical Bowl Cost Estimating Study, SAND82-7111, March 1982.



Figure 5-2. Receiver Assembly of the Hemispherical Bowl in Crosbyton. The water inlet and steam output lines are visible in the foreground.



The most significant technical problem identified during bowl operation has been the so-called "mirror hot-spot." The mirror facets at the base of the focal line have absorbed enough energy to heat and crack from thermal stress. This problem only occurs when the receiver is not in tracking position to absorb reflected energy and so is not a daily problem. Preventive measures such as shading devices or active cooling systems are being examined, but major emphasis has been on developing a mirror panel capable of withstanding the condition without active protection. Specially instrumented panels have been installed in the bowl system to quantify the problem. The bowl is also being used as a test bed to evaluate the durability of alternate mirror facets. An alternate facet employing aluminum honeycomb core has shown improved resistance to the hot spot, but continued investigation is needed.

Other significant investigations have included the development of lower cost components, e.g., larger individual facets and a concept called the "super panel," which consists of large multi-faceted, factory-assembled panels. The super panel would reduce the amount of field labor at a bowl construction site by permitting the workmen to install a much larger area of reflective surface in a single operation.

## B. SALT-GRADIENT SOLAR POND TECHNOLOGY

Research addressing a number of technical problems and issues relating to salt-gradient solar ponds continued in FY 1982. The rate of extraction of mass and heat from solar ponds, development of a direct contact heat exchanger, and a study of ways to control the gradient layer of solar ponds have been recognized as research areas of critical importance in the development of a salt-gradient solar pond technology base. Solar pond research and development is now at a point where the technical and economic feasibility of constructing a large solar pond power plant can be considered. At the beginning of FY 1982, two feasibility studies were in progress, one for the Salton Sea in California and one for the Truscott Brine Lake in Texas. Two other sites were also being considered in less detail: the Great Salt Lake and the basin of the lower Colorado River. A two-year study was initiated to compare the four sites and identify the most suitable location for the development of a large (5-MWe) engineering test facility.

### 1. Analysis and Supporting Research

a. Heat and Mass Extraction. Heat is extracted from a solar pond by continuously or intermittently withdrawing hot brine from the storage layer, circulating it through an external heat exchanger, and returning cool brine to the storage layer. There is a flow of brine within the storage layer from the return port to the withdrawal port. At the boundary between the storage layer and the gradient layer, the horizontal water motion decreases from its value in the storage layer to zero, creating a sheer force on the interface between the gradient layer and the storage layer. If this force is strong enough, it can disturb the interface and cause mixing of the two layers. This erosion of the gradient layer from below will decrease the thickness of the gradient layer. When the thickness of the gradient layer decreases, its insulating value drops, and there will be a corresponding drop in the operating

temperature of the solar pond. In order to prevent this from occurring, it is necessary to identify the optimal locations for withdrawal and return ports and the maximum rate at which heat can be withdrawn while ensuring gradient stability.

The dynamics of heat and mass extraction from solar ponds have been under investigation at the Solar Energy Research Institute (SERI). The approach has been to simulate relevant features of a vertical slice of a solar pond in the laboratory and correlate the rate of erosion of the gradient layer from below to parameters characterizing the withdrawal and return port locations and the rate of heat extraction. After these parameters are verified by tests conducted in a large research pond, results from the laboratory investigations can be used by designers of full-scale solar ponds.

In FY 1982, a laboratory facility to simulate a vertical slice of a solar pond was constructed and instrumented. This facility features a sealed rectangular tank 1 m wide by 2 m deep and 10 m long (Figures 5-3 and 5-4). The tank is electrically heated from the bottom and has removable injection and withdrawal manifolds consisting of adjustable slots that cover the width of the tank. Density is determined by measuring the weight of a body of known mass and dimensions immersed in the brine. The position of the interface between the gradient and storage layers is determined by a rate of closely spaced thermistors positioned to span it. The rate of mass recirculation is measured by a flow meter, and brine inlet and outlet temperatures are measured by a platinum resistance thermometer located in the injection and withdrawal ports.

Operation of the facility was verified, and initial tests on heat and mass extraction under simulated pond conditions have been performed. The heat balance of the tank was determined and source and gradient layers established. Figure 5-5 shows the vertical temperature and density distribution in the tank under one set of operating conditions. In FY 1983, laboratory tests are planned to determine the physical factors that limit the rate at which heat and mass may be withdrawn from the storage layer by examining the extraction method currently used in most existing solar ponds.

b. Direct Contact Heat Exchange Research. Heat collected and stored by a solar pond may be used to drive a heat engine to produce mechanical or electrical power. Conventional technology uses a surface contact heat exchanger to couple the solar pond to an organic Rankine power cycle. Because the temperature difference between the pond and the atmosphere is small, the surface heat exchanger (which could amount to 25% of the capital cost of all the power conversion equipment excluding the pond) must have a large surface area. A direct contact heat exchanger that would eliminate the bulk of the material in a surface heat exchanger could reduce the cost of this component to a negligible amount. The direct contact heat exchanger concept being pursued operates by introducing drops of the organic working fluid at the base of a vertical column filled with hot brine from the pond flowing in the top and out the bottom. The drops of organic fluid are lighter than the brine and rise up the column, absorbing heat from the brine. The drops are evaporated as they rise through the column, and heated organic fluid vapor exits from the top.

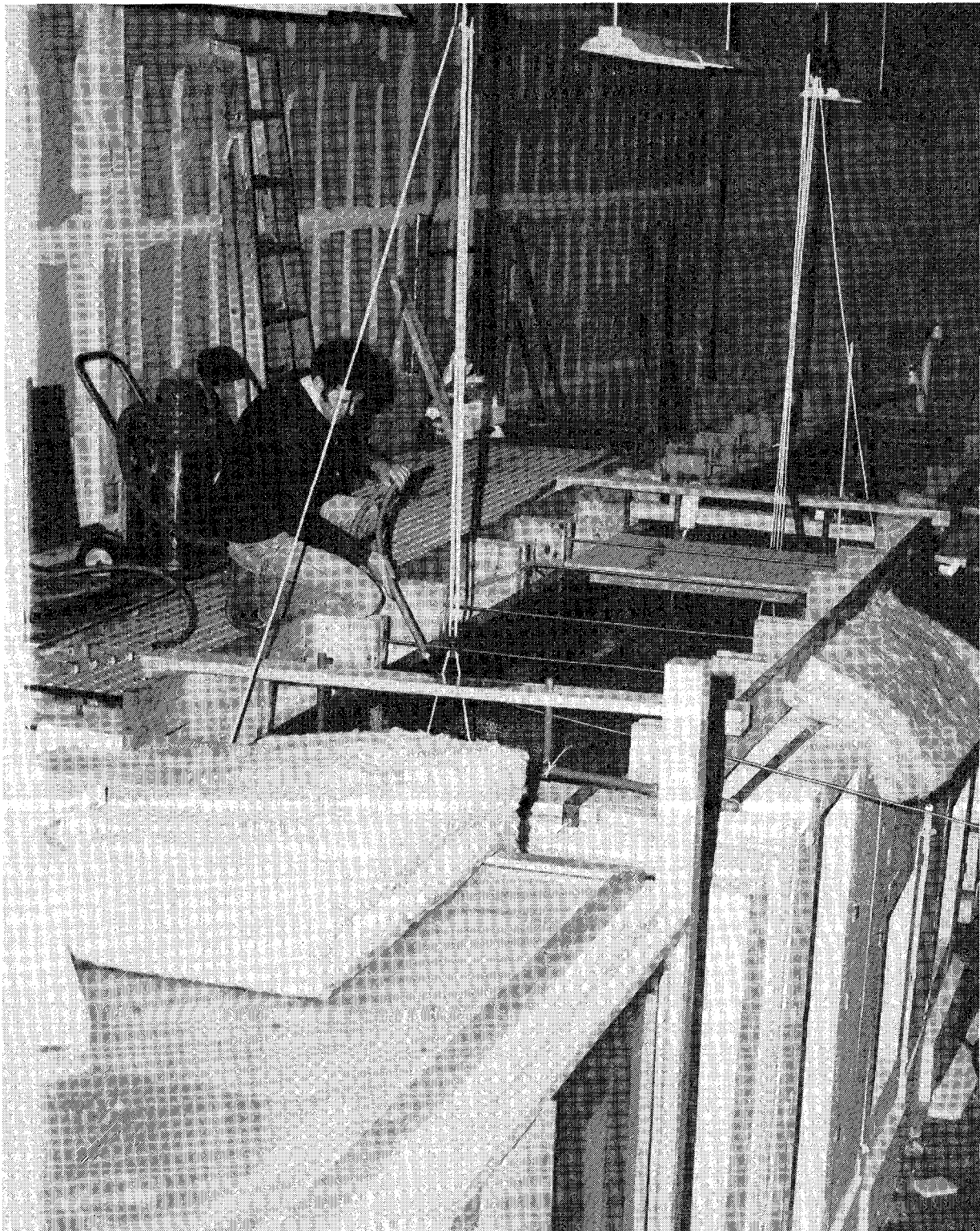


Figure 5-3. SERI Laboratory Test Tank Simulating a Vertical Slice of Solar Pond

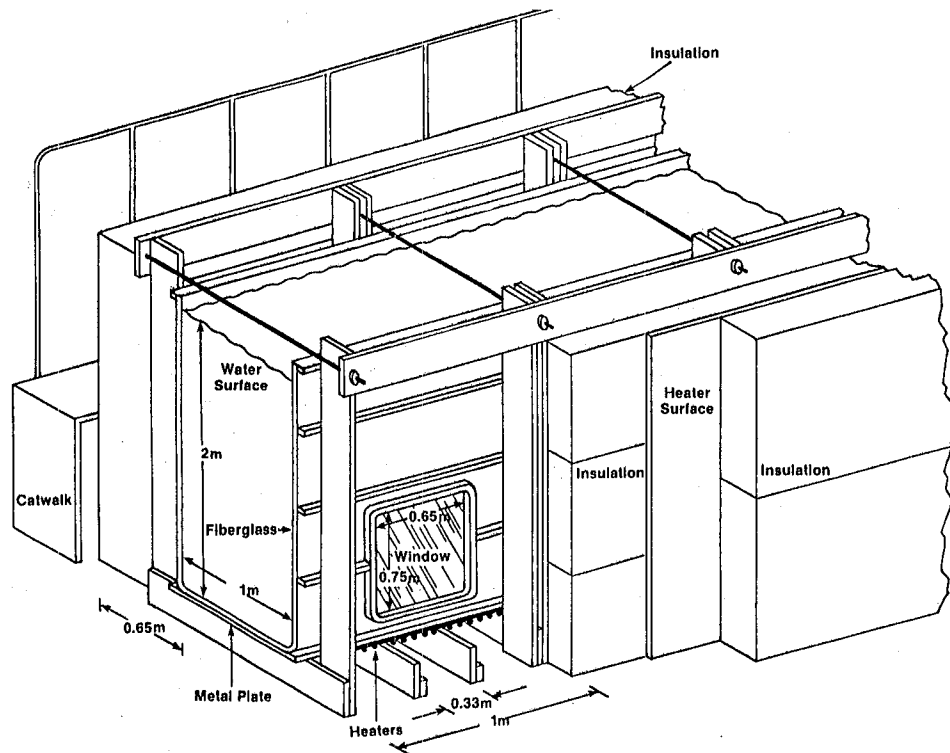


Figure 5-4. Cutaway Diagram of SERI Solar Pond Test Tank

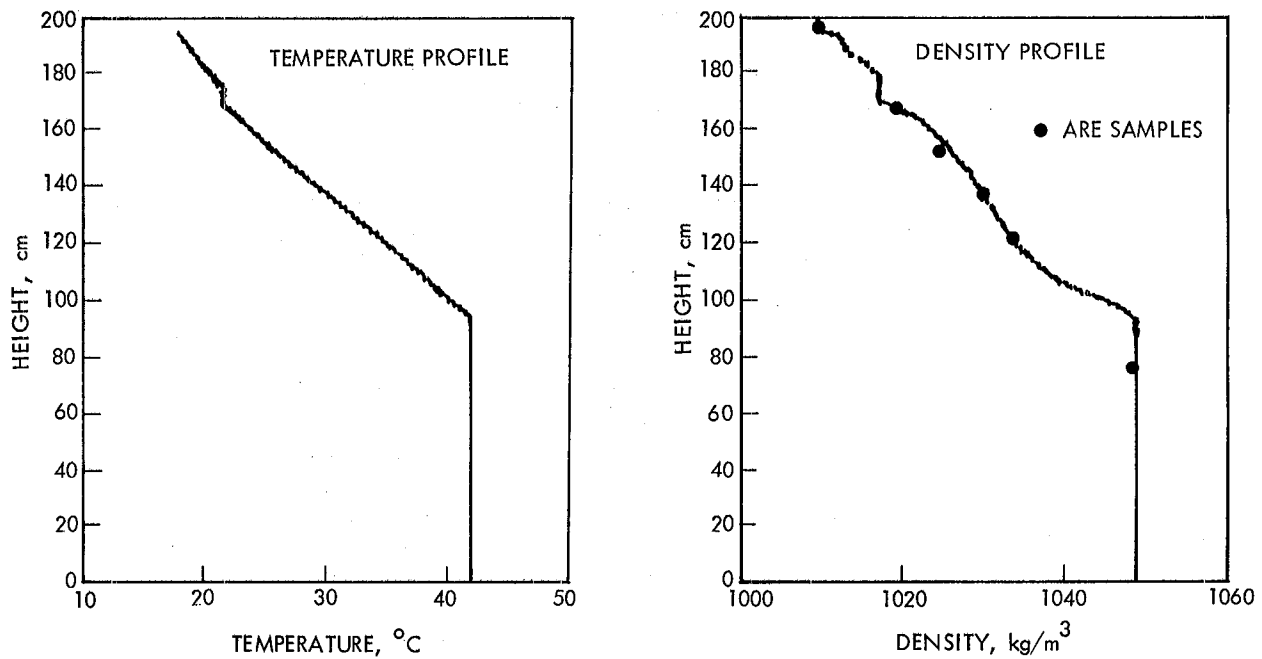


Figure 5-5. Vertical Temperature and Density Distribution in the Pond Slice

With support from the Department of the Interior and the Bureau of Reclamation, SERI has been working to develop this direct contact heat exchanger concept. During FY 1981, preliminary designs having economic potential and displaying technical merit were identified by analysis, and a suitable working fluid was selected as a result of a trade-off between parasitic power losses and pressure in the Rankine cycle. A conceptual design of a direct contact heat exchanger was developed using existing data, and areas for future research were identified.

In FY 1982, under support from DOE, laboratory setups to measure bulk heat transfer coefficients and maximum flow-through rates in packed and unpacked columns were designed. Two measurement facilities are planned: a 2-ft-diameter column at the University of Utah and a 6-in.-diameter column at SERI. Measurements from both columns will be compared to verify methods of extrapolating results to a full-scale heat exchanger. Objectives for FY 1983 are to complete laboratory testing and to initiate design of a full-scale heat exchanger.

c. Gradient Layer Control and Maintenance. The gradient layer of a solar pond allows the storage layer to reach a high temperature by preventing convection within the gradient layer so that heat transfer through it from the storage layer to the surface is by conduction only. Convection is prevented by creating a stable density distribution within the gradient layer by establishing a stable distribution of salt. However, temperature also changes through the gradient layer from a high value in the storage layer to nearly ambient at the surface. If the local gradient of temperature becomes too large compared to the local gradient of salt, the density distribution will become unstable and local mixing will result. When this occurs, the insulating value of the gradient layer is effectively reduced in proportion to the thickness of the undesired mixed layer. Instabilities and resultant mixing also can occur due to heat fluxes through the sides of the gradient layer. It is likely that during the approximate 30-year lifetime of an operating solar pond, problems will be encountered in maintaining the gradient layer. Mixing events can be severe enough to warrant either preventing instabilities causing them or repairing the gradient layer after a mixing event has occurred.

SERI has begun to develop gradient layer control and maintenance procedures and equipment. In FY 1982, literature on the behavior of fluids with a stable salt distribution and an unstable temperature distribution was reviewed in order to catalog the mechanisms causing instabilities and the characteristics of the resulting mixed regions. It was discovered that two conditions affecting solar ponds have not been investigated: (1) the effect of non-linear distributions of temperature and salt and (2) the effect of lateral heat flux through the walls when the interior of the fluid has an unstable temperature distribution as well as a stable salt distribution. To characterize these conditions, a stratified fluid test tank was built with support from the DOE Active Heating and Cooling (AHAC) Program. The tank (Figure 5-6) is heated from above by solar simulators to provide a nonlinear distribution of salt. Heat flux through the walls is controlled by insulation and guard heaters, and the tank is instrumented with a density probe and temperature sensors. Mixed regions of the gradient are observed with a shadow graph. Objectives for FY 1983 are to complete the exploratory experiments with this small tank and design gradient layer control maintenance procedures and equipment for a full-sized pond.

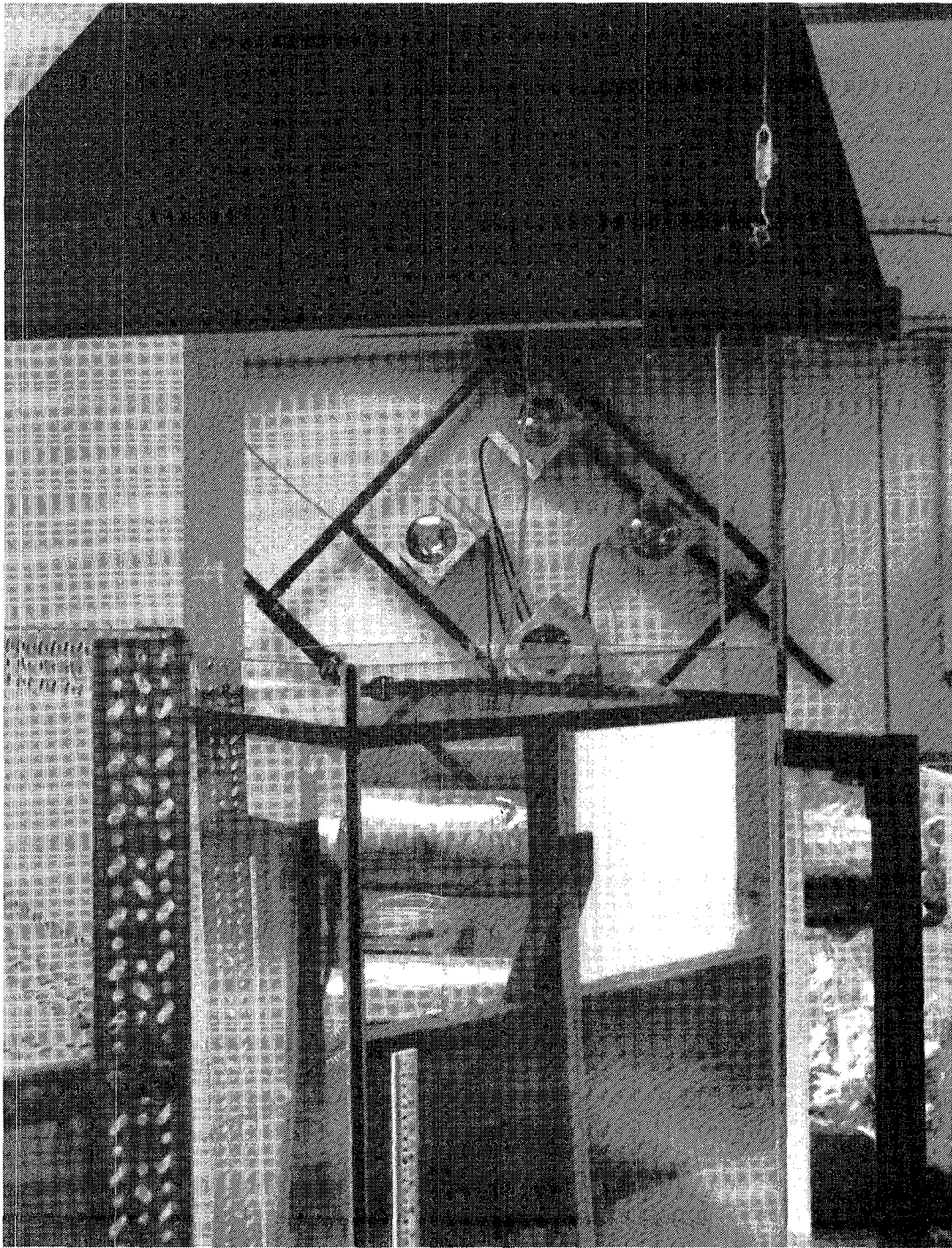


Figure 5-6. Stratified Fluid Test Tank



## 2. System Analysis and Benefit Assessment

Construction of a large solar salt-gradient pond power plant for demonstrating commercial viability has become feasible given the current state of solar pond research and development. At the beginning of FY 1982, two feasibility studies were in progress: The Jet Propulsion Laboratory was investigating the Salton Sea in Southern California, and the U.S. Army Corps of Engineers was considering the Truscott Brine Lake in west Texas. The Great Salt Lake and locations along the lower Colorado River were also suggested as possible sites. A system analysis and benefit assessment conducted by Pacific Northwest Laboratory (PNL) ultimately will compare these four sites and identify the most suitable site for a large (5-MWe) engineering test facility.

The FY 1982 objectives of the system analysis and benefit assessment were to

- (1) Work with the U.S. Army Corps of Engineers to evaluate the technical and economic feasibility of a salt-gradient pond power plant located at Truscott Brine Lake and submit a report to Congress documenting the results.
- (2) Investigate the technical and economic feasibility of a salt-gradient pond power plant located at the Great Salt Lake.
- (3) Compare the Truscott Brine Lake and Great Salt Lake studies with similar studies for the Salton Sea and the Lower Colorado River Basin and identify the most suitable site for future development.
- (4) Assemble a salt-gradient pond design handbook.

Objectives 1 and 2 were completed in FY 1982 while items 3 and 4 are planned for FY 1983.

The FY 1982 effort emphasized completion of the feasibility studies for the Truscott Brine Lake and Great Salt Lake and development of ground rules and criteria for site comparison. FY 1982 accomplishments for the system analysis and benefit assessment are described in the following paragraphs.

a. Truscott Brine Lake Feasibility Study. Using the results of the design and cost study conducted by the U.S. Army Corps of Engineers, PNL determined the technical and economic feasibility of locating a salt-gradient pond power plant at Truscott Brine Lake. A report to Congress<sup>6</sup> documented the results. The study indicated that the project was technically feasible, given the current understanding of salt pond phenomena, but marginally uneconomical. Continued research will narrow the technical and economic uncertainties.

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<sup>6</sup>"The Technical and Economic Feasibility of Salt-Gradient Solar Ponds at the Truscott Brine Lake of the Red River Chloride Control Project -- A Report to the House-Senate Committee on Appropriations of the 97th Congress," PNL 4396, a joint publication of the Tulsa District U.S. Corps of Engineers and Pacific Northwest Laboratory, September 1982.

b. Development of Design Techniques. A unique optimization methodology was developed to design a solar pond power plant as part of the Great Salt Lake feasibility study. This technique involved the simultaneous optimization of the entire pond power plant, including solar and evaporation ponds, heat engine, and piping systems. The technique was based on the levelized energy cost, an economic rather than thermodynamic figure of merit.

The methodology involved the use of four different computer codes: SOLPOND, developed at SERI to model the pond thermal performance; GCOST, developed at PNL to model the heat engine; ETRANS, developed at PNL to model the piping systems; and an economic model to cost components and calculate a levelized energy cost. These existing codes provide a valuable foundation upon which to build a total system optimization code in FY 1983. This code will be valuable for extrapolating experimental data collected at test ponds to other sites around the country, for determining optimal solar pond power plant designs for local sites and applications, and for determining the cost effectiveness of new components and design modifications (e.g., water treatment, upper convective zone maintenance, direct contact heat exchangers, and pond liners).

c. Definition of the Great Salt Lake Design. Using the techniques described above, an economically optimal design for the Great Salt Lake was developed.<sup>7</sup> Its key features are presented in Table 5-1. Some of the unique features for the plant produced by the economic optimization procedure are listed below:

- (1) A relatively shallow storage zone was selected. Although deeper storage zones are more thermodynamically efficient, the costs of a deeper pond and larger evaporation pond could not be offset over the life of the plant.
- (2) Ammonia was selected as the working fluid. Although several other organic fluids appeared more thermodynamically favorable, the heat transfer properties of ammonia reduce heat exchanger costs, and ammonia is less expensive.
- (3) The levelized energy cost calculated for this optimal 5-MWe low capacity factor power plant is 288 mills/kWh. Extrapolating this cost to commercial-size plants results in a levelized energy cost below 100 mills/kWh.

d. Completion of Site Comparison Methods. Ground rules and evaluation criteria were established for the site comparison study. Inputs from several solar pond research groups including JPL, SERI, the U.S. Army Corps of Engineers, and various other independent researchers were coordinated.

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<sup>7</sup>Drost, M. K., et al, "Optimization and Preconceptual Design of a 5-MWe Salt-Gradient Pond Power Plant at Great Salt Lake," PNL 4667, Pacific Northwest Laboratory, May 1983.



Table 5-1. Great Salt Lake Design Characteristics

Characteristic	Design Specification
Pond Size, hectare	61.8
Upper Convecting Zone Thickness, m	0.4
Gradient Zone Thickness, m	1.25
Storage Zone Thickness, m	1.0
Average Annual Pond Temperature, °C	86
Heat Engine Gross Output, MWe	5
Capacity Factor	0.228
Heat Engine Working Fluid	Ammonia
Heat Engine Efficiency, gross	8.63
Capital Cost, 1982 dollars	14,300,000
Levelized Energy Cost, mills/kWh, 1982 dollars	288

The development of effective systems analysis tools, in conjunction with fundamental research, is necessary to further develop solar pond technology. The system analysis and benefit assessment effort has established the basis for an integrated system optimization approach for solar pond power plants.

### 3. Salt-Gradient Solar Pond Systems Experiment: Salton Sea Site-Specific Studies

The activities planned for the Salton Sea Solar Pond Project in FY 1982 consisted of a detailed design of a 5-MWe power plant and supporting site specific studies. The detailed design portion of the effort was to be cost shared by the Department of Energy, Southern California Edison Company, and the California Energy Commission. Due to changing economic conditions and a divergence of institutional objectives, the joint sponsorship was dissolved.

During FY 1982, Salton Sea site-specific studies were carried out under DOE sponsorship. These studies, discussed below, support the continuation of a design study planned by DOE for FY 1983.

a. Light Transmission. Solar pond performance is very sensitive to the transmission of radiant energy through the top layers of the pond and into the lower storage zone. Water from the Salton Sea contains dissolved substances and suspended matter that absorbs and scatters radiant energy. During 1980, this problem was identified, and water clarification treatments were investigated. Filtration and treatment with activated carbon were found to produce a substantial improvement in water clarity.

Extrapolation of laboratory clarity measurements to real pond behavior can produce uncertainties. Forward-scattering of light in the Cary 14 spectrophotometer and the multiplying effects of mathematical extrapolations as an error source that could be as high as 25% were identified.<sup>8</sup> Research to improve the techniques of measuring light transmission was also undertaken during this fiscal year. Key elements of this research included use of actual (rather than artificial) solar radiation and a test fixture geometry that would not exclude forward-scattered light.

A test apparatus was assembled and some preliminary tests conducted. Preliminary results confirm the effect of path length on light transmission and, surprisingly, show unconcentrated Salton Sea water to have better than expected transmission characteristics.

b. Water Treatment. Investigative analyses and experiments were conducted to satisfy the following objectives: (1) evaluate water treatment processes for decolorizing that do not depend on activated carbon, (2) investigate the substitution of standard commercial water analysis procedures for the spectrophotometric method, and (3) develop requirement specifications for the optical quality of treated Salton Sea brine.

Ozone treatment was found to be as effective as activated carbon in removing color from Salton Sea water.<sup>9</sup> Dual treatment with both activated carbon and ozone was found to produce better results than either process alone. A representative group of flocculants were also tested, but none were found to be effective.

Salton Sea water samples were prepared and tested for color and turbidity in a commercial laboratory.<sup>10</sup> The data from the color tests correlated with spectrophotometric data, but the turbidity measurements did not correlate. This means that the standard commercial color test is suitable for design and

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<sup>8</sup>Giullianelli, J., The Spectrophotometric Method of Determining the Transmission of Solar Energy in Salt Gradient Solar Ponds, Final Report, DOE-ASEE Summer Faculty Research Fellow, 1981.

<sup>9</sup>Carpenter, S., et al, Water Treatment for Salt-Gradient Solar Ponds at the Salton Sea, Final Report, DOE-ASEE Summer Faculty Research Fellow, 1981.

<sup>10</sup>Standard Methods for the Examination of Water and Wastewater, Methods 204A for Color and 214A for Turbidity, 15th Edition, 1980.

operation of the decolorization process. For turbidity, the spectrophotometric measurement remains the most promising technique. Spectrophotometric measurements remain the measurement of choice for research work because the data are not integrated to a single value and readily display small differences in characteristics.

c. Brine/Soil Suitability. Laboratory testing of Salton Sea soils and brines have continued with emphasis placed on microbiological reactions, soil induced contamination of the solar pond, and permeation rates of the local clay.

Improved testing to better simulate the pond warmup time/temperature profile produced no damaging microbiological gas evolution. These results are a positive indication that a solar pond can be constructed and operated at the Salton Sea site.

Exploratory tests indicate that soil will produce light-attenuating contamination in the brine. In the laboratory test fixture, most of the change occurred in the first month. Further testing will be required to better quantify the effect and to develop solutions if the contamination appears to significantly degrade pond performance.

The ability of the local clay to adequately seal the bottom of the solar pond is a critical item. Permeation coefficients below  $1 \times 10^{-6}$  cm/sec are desirable. Preliminary tests of some samples indicate good permeation quality over a short time interval at room temperature. A single test using concentrated brine and a time varying temperature indicated significant degradation of sealing quality at temperatures above 70°C (158°F). Further experiments are needed to determine long-term permeation rates under solar pond conditions and to determine soil lining design requirements.

d. Corrosion. Exploratory corrosion tests were conducted. Mild and stainless steels were tested in representative surface and storage layer brines. All materials show some effects. The results are not conclusive, but indicate that a corrosion resistant material will be necessary for the condensing heat exchangers. A mild steel may be acceptable for the evaporative heat exchangers.

## C. AGRICULTURAL PROCESS HEAT TECHNOLOGY

During FY 1982, active and passive solar thermal systems were successfully demonstrated throughout the United States in a number of agricultural applications, including greenhouse heating, crop drying, food processing, and heating for livestock shelters.

Tests were completed to demonstrate the effect of operating a greenhouse night curtain based on light level rather than time of day (time clock control). When a total solar insolation inside the greenhouse of 30 W/m<sup>2</sup> was used as the point to operate the curtain, an additional overall saving of 10% in heating needs was measured. A loss in total light of 3 to 4% was measured, indicating minimal negative effect on plant growth.

Tomatoes were grown from February 15 to July 1 and from September 1 to January 1 in solar heated soil in a special heat-conserving greenhouse to determine the effects on plant growth and production rates. Tomato yields in the late winter and early spring were greater than the control planting in the same greenhouse without heated soil. Solar energy was the source of about 95% of the heat required for this planting. However, the fall planting of tomatoes did not yield as much as the late winter planting. The plants grew rapidly through October, but a decrease in solar energy in November slowed the maturation rate.

A combination of Tefzel heat-absorbing glass greenhouse panels with water flowing through the panels as the heat collecting medium allowed 61 to 67% light transmittance, depending upon the presence of internal condensation on the film. As a solar collector, the efficiency appears to be about 40%.

A solar hot-air collector system was constructed for direct surface drying of fresh citrus or for regenerating solid desiccants. For either the desiccant regeneration or fruit drying mode, collector efficiencies averaged 44.1%, with an overall efficiency for desiccant regeneration of 12.3%. Economic comparison of activated alumina and silica gel yielded cost estimates of 6.15\$/kg-H<sub>2</sub>O removal (activated alumina) and 8.11\$/kg-H<sub>2</sub>O removal (silica gel).

A solar brooding system, consisting of a 96-ft-long cylindrical, line concentrating, pressure stabilized collector (CLCPSC) with a 2000-gal heat storage exchanger was operated in an unattended mode throughout the year. The best recorded performance has been during the winter months when collector outlet temperatures reached 89°C (192°F). Instantaneous thermal efficiency rose to 71% in December, and peak collector output was 22.5 kWt (76,800 Btu/h) in February.

One drying test in late September, using a multi-use modular dryer, included a full complement of 32 large round bales of lespedeza-fescue hay. The test extended over a 5-day period of mostly inclement weather (only 2 fair days, which were not consecutive). The drying rate during the one completely fair day was 6.5 percentage points per day.

Three concepts have been successfully tested for regenerating (reconcentrating) liquid desiccant using the sun: (1) an integral solar collector and mass/heat transfer device, (2) a separate solar heated air collector, and (3) an open flow solar heated liquid. Because thermal degradation is not a problem when using the liquid desiccant, solar energy may be stored over long periods of time. This long storage period allows the collector size to be reduced to about 10% of the size recommended when thermal degradation must be considered. The concentrated liquid desiccant is used to dehumidify air that in turn is used to dry the crop in a closed loop system. This system is unique because it can dry crops during periods of high humidity and no sun and requires no backup heating system.

A multiple-use solar system was designed using a solar hop drying installation to supplement the heating requirements of an adjacent 325-m<sup>2</sup> fiberglass greenhouse. The area under the workbench in the greenhouse was enclosed and filled with rocks to provide thermal storage. Monitoring

instrumentation was incorporated in the rocks. Performance of the system indicated that 37% of the annual heating load could be met using solar energy. Economic analysis predicted a 10-year payback period.

Design criteria for solar drying systems were developed using computer simulations (modified TRNSYS). Designing for a 50% solar requirement and a storage temperature recovery of up to 40°C (104°F) over a 3-day cycle for one wagon (4.72 Mg), resulted in system component sizes of 156 m<sup>2</sup> for the collector, 56 m<sup>3</sup> for storage (air/rock system), and 128 m<sup>2</sup> and 22 m<sup>3</sup> for the water system. During experimental tests where the air flow was interrupted for 15 minutes each hour, energy use was reduced 20% with little increase in drying time. Experiments to partially recycle the drying air produced energy savings of 50 to 70%, but drying time was increased by 24 hours and high moisture peanuts showed some white mold growth.

Total fruit weight from the spring crop of tomatoes grown in an experimental greenhouse (using exhaust air rich in CO<sub>2</sub> from a swine house) was nearly twice the amount from plants in a control greenhouse. Fruit defects (radial cracking most prevalent) was more common in the experimental greenhouse, resulting in only a 6% higher yield in marketable fruit. On May 1, bedding transplants from the experimental greenhouse were approximately twice as large as those from the control greenhouse based on dry weight. During the Spring 1982 growing season, the experimental greenhouse used only 20% as much fuel as the control greenhouse.

Operation during a third winter has confirmed the feasibility of using solar energy to provide a thermal environment appropriate for young pigs (7 to 23 kg). Passive collectors that double as openable ventilation panels along the high south wall of the mono-slope roof building provide quick response on sunny days by heating the front two-thirds of the pens. An active collector positioned at ground level across the front of the building provides warm air to heat the animal sleeping space (rear third of pens) through an in-floor heat distribution/storage system. The design resulted in acceptable sleeping space temperatures even when overcast weather occurred for periods of up to one week.

Drying experiments were conducted on papaya and banana slices (6 ± 0.2 mm thick) with a hybrid solar-biogas system operating from morning through evening hours. An advantage of the solar-biogas system over the solar-only system is that the former completes drying in less than a day while the latter requires 2 sunny days; drying rates and air temperature are better controlled; and the quality of dried fruit from the hybrid system is superior to that of fruit from the solar-only system.

## SECTION VI

### RESEARCH

The Solar Thermal Technology Program research effort is organized to conduct long-term/high-risk research with potential high-payoff as well as to provide necessary support for near- and mid-term technology development. Investigations of advanced materials for high-temperature systems, polymeric materials for low-cost concentrators, characterization of reflector materials, and research of advanced concepts are being pursued by industry, national laboratories, and universities.

#### A. MATERIALS RESEARCH

##### 1. Testing Silver Mirrors

Accelerated durability testing of mirrors for concentrator applications was continued in FY 1982 at the Solar Energy Research Institute (SERI) and Pacific Northwest Laboratory (PNL). Of the two project goals, the near-term goal of developing a test for ranking the relative durability of commercially and laboratory prepared mirrors was achieved. The second goal, development of a methodology for predicting the service life of mirrors based on the survival time in an accelerated test to understand the mechanisms of mirror degradation, was partially achieved.

In FY 1981, data were obtained for degradation rates of mirrors exposed to 80°C (176°F) water vapor and temperature cycling, and four optical characterization techniques were identified to adequately characterize degradation in mirror performance. In FY 1982, exposures were extended to include several additional parameters: ultraviolet (UV) light, elevated temperature, humidified pollutants, and mechanical stress. The level of each exposure parameter and the estimated acceleration factor relative to typical natural exposures are given in Table 6-1. At SERI, specimens of four different commercially produced silver/glass mirrors were subjected to exposure of up to six week's ultraviolet light at various elevated temperatures and to humidified environments containing pollutant gases by using custom-designed exposure boxes that were placed in a Weather-O-Meter. Data on the light scattering properties and reflectance of these specimens were obtained using image analysis of the microstructure observed with darkfield illumination. Optical reflectance values were obtained by use of an integrating sphere reflectometer. At PNL, specimens of two different mirrors were subjected to static mechanical stress, high and low humidity, and various temperatures using a similar procedure. Data on the degradation of these specimens were collected using spectral, hemispherical, and diffuse reflectance between 200 and 2600 nm. All data were subjected to statistical analysis of variance to extract significant differences in degradation rates due to individual and combinations of the parameters imposed.

Table 6-1. Exposure Conditions for Accelerated Mirror Testing

Parameter	Level	Factor Exceeding Typical Solar Environment
Temperature, °C (°K)	Up to 100 (373)	1.25 - ??(a)
Relative Humidity, %	5 to 100	1
Pollutants, ppm		
NO <sub>2</sub>	5	~500
NO	83	~4000
SO <sub>2</sub>	7	~7000
Cl	3	1000(b)
Ultraviolet, $\mu\text{W}/\text{cm}^2/\text{nm}$		
325 nm	20	1
310 nm	10	10
305 nm	10	100
Mechanical Stress	40% of the breaking point of glass	~5

<sup>a</sup>While the temperature is about 1.25 times that in a solar environment, its acceleration factor cannot be estimated without knowing the mechanism of the rate controlling degradation.

<sup>b</sup>Estimate.

Nine important conclusions were drawn from this research:

- (1) Considerable variation exists in degradation rates among mirror specimens taken from the same source. This nonuniformity in mirrors produced by the commercial electroless silvering process requires at least three specimens in each set to secure even marginally acceptable statistics.
- (2) The specular reflectance at a wavelength near 400 nm is a single sensitive optical measure of mirror degradation for specimens with flat glass superstrates. Correlating this specular reflectance to solar weighted reflectance will require additional work.
- (3) The rate of mirror degradation is very temperature sensitive. Degradation at temperatures greater than 90°C (194°F) is dominated by rapid agglomeration of the silver in the reflective layer. Activation energies for agglomeration are much less in

mirrors prepared by the electroless commercial process than in vapor processed and dielectric protected mirrors. At less than 80°C (176°F), the degradation rate is slower and may be due primarily to chemical reactions. Determining the rates for these reactions and identifying the rate controlling processes at various temperatures require further research.

- (4) Degradation of commercially prepared mirrors is faster at 100% relative humidity (RH) when water condenses on the specimens. At RH values below about 75%, where condensation is minimal, the degradation rates do not appear sensitive to relative humidity.
- (5) Mirror specimens exposed to pollutant gases degraded slower than those exposed to water vapor alone. Because this probably resulted from purging oxygen and lowering the humidity by a nitrogen carrier gas, any accelerated degradation caused by pollutants alone remains to be determined.
- (6) Mirrors prepared by the commercial electroless process did not show statistically significant acceleration of degradation in solar reflectance after six week's exposure to UV light. However, a decrease in the spectral reflectance below 350 nm was correlated to UV exposure and most probably results from a decrease in the transmittance of the glass superstrate. The long-term significance of this UV effect on glass and the solar reflectance of the mirror is not known.
- (7) No differences were observed in the degradation rate of mirrors subjected to static mechanical stress at levels up to 40% of the glass breaking point in a number of environments compared to the unstressed control specimens in the same environments.
- (8) The ability to rank the relative durability of mirrors using accelerated test conditions was improved during FY 1982. Correlation of accelerated test results to those of field testing will require additional work.
- (9) The availability of specimens for study and the results of the accelerated testing experiments have contributed to deducing the chemical models of degradation discussed in Section VI.A.2 below.

## 2. Degradation Mechanisms in Silver/Glass Mirrors

Mirrors made by the electroless process consist of a multi-layer stack of glass, Ag, Cu, and paint. Surface analytical techniques were used to analyze the elemental composition at the Ag/glass, Ag/Cu, and Cu/paint interfaces as well as the impurities present in each layer of the mirror. A tin complex has been proposed as the initial configuration of tin on the glass surface prior to silver plating; the model is consistent with data obtained and in the literature. Results of studies of complete mirror stacks and of partially made mirrors prepared at SERI reveal that some sensitizer and Ag



reducer solution components are trapped during mirror formation at the Ag/glass interface and that Cu reducer solution components are trapped at the Cu/paint interface. After real-time and accelerated life testing of complete mirrors, large amounts of chloride were identified at the Cu/paint interface. The source of this chloride is still not defined. Results from samples aged for six months and one year show that iron from the glass segregates to the Ag/glass interface; Cu diffuses into the Ag layer to the Ag/glass interface; and oxygen penetrates into the Cu layer from the Cu/paint interface and/or Cu/air interface. Impurities identified at the various interfaces are shown in Figure 6-1.

Given the existence of impurities at the Cu/paint and Ag/glass interfaces and the occurrence of water permeation of the paint backing, electromechanical calculations predict that copper will corrode in basic solutions and that silver corrosion will occur in acidic solutions. With chloride present, both layers corrode at any pH. With the present methods of manufacture, the combination of water, oxygen, and impurities guarantees that corrosion of mirrors will occur. The time-to-failure cannot be predicted from the limited data taken; additional research is required to establish the rate controlling mechanisms that result in mirror degradation.

For long-life mirrors, further research is required to (1) find a way to eliminate the impurities in commercially made mirrors, (2) eliminate water and/or oxygen from mirror modules, or (3) develop an advanced mirror made by a different process where the variables of manufacture can be controlled more easily.

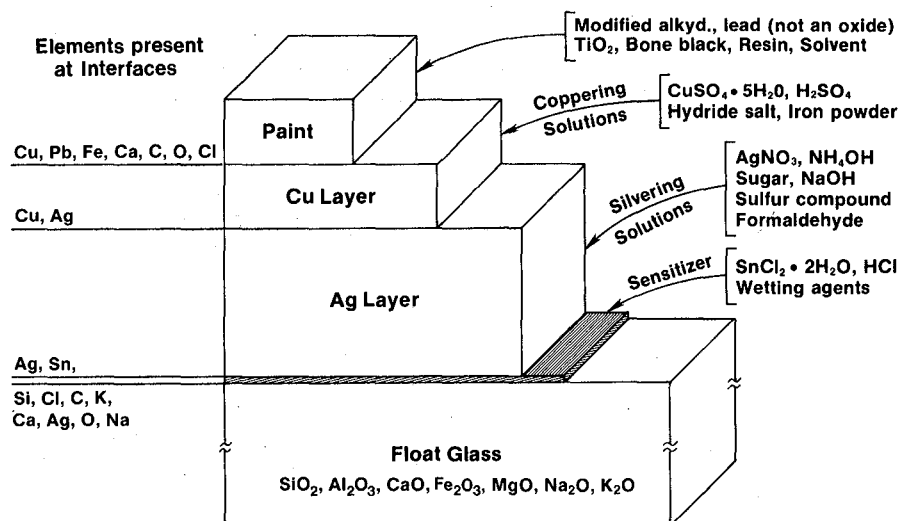


Figure 6-1. Impurities at the Ag/Glass, Ag/Cu, and Cu/Paint Interfaces of Silver/Glass Mirrors

### 3. Advanced Silver/Glass Mirrors

Work began in FY 1981 on testing several advanced mirror concepts. This work was completed in FY 1982. Mirrors were prepared by thermal evaporation, magnetron sputtering, and decomposing organometallic solutions on different substrates with different backing materials with and without paint. The mirrors were subjected to salt spray, acid vapor, and the accelerated tests described in Section VI.A.1. While most of these mirrors could not survive the salt spray and acid vapor tests, four mirrors with an Inconel 600 backing (unpainted) did survive the severe accelerated tests. None of the mirrors exhibited a durability comparable to those made using the wet process method with a paint backing, although failures in the test batch were primarily at the Ag/glass interface. Developing a durable adhesion layer between Ag and glass and studying mirrors backed by Inconel are logical extensions of the advanced mirror testing program.

Based on the experience described above (Sections VI.A.1 and 2), a patent disclosure for preparing a potentially long-life silver mirror was formulated. If long-life potential can be demonstrated on a laboratory scale, the mirror could be produced in large quantities using existing vacuum metallurgical technology.

### 4. Fracture Behavior of Solar Glasses

The fracture toughness,  $K_{IC}$ , and stress corrosion properties of Corning 7809 glass were evaluated. The value of  $K_{IC}$  was  $0.795 \pm 0.02 \text{ MPa (m}^{1/2}\text{)}$ , about 3% greater than for soda-lime float glass, thus making 7809 glass equally resistant to hail impact and handling. The stress corrosion coefficient was estimated to be 44, compared to 19 for float glass. This indicates that 7809 glass (developed by Corning with support from the DOE STT Program and which can be drawn into very thin sheets) will be better able than float glass to resist the growth of cracks, which lead to delayed failure when the glass is held in tension for elastic formation into a linear parabolic mirror.

The fracture behavior of Corning 7809 and float glass were also studied after developing a computer assisted control and data acquisition system to operate a fractometer. For crack velocities below  $10^{-7} \text{ m/sec}$ , where delayed failure could be expected in an application such as elastically formed thin glass mirrors, the crack growth rate is slower in 7809 glass than in float glass. Critical stress intensity factors were also evaluated using the improved equipment, which also will be used for testing high temperature ceramic materials during FY 1983 and beyond.

### 5. Metallized Polymers

Seven combinations of commercially available aluminum or silver metallized polymers were subjected to accelerated testing at  $80^\circ\text{C}$  ( $176^\circ\text{F}$ ) in UV and humidified pollutants at SERI as discussed in Section VI.A.1. The substrate polymers included teflon, acrylic, polycarbonate, and silicon silicate; the backing materials were polyester, acrylic, mylar, or Inconel.

All the silver polymers proved much less durable than the aluminized polymers. The 3M Company's aluminized products (YS-91A and FEK-244) appeared to best withstand accelerated testing. Further research will be required to understand the degradation mechanisms in silvered polymers for ultimately achieving the benefits of increased silver reflectance. Research in this area, initiated in FY 1982, will continue in FY 1983.

## B. ADVANCED COMPONENTS

### 1. High-Temperature Receivers

Central receiver systems currently under development use intermediate-temperature molten nitrate salts as the heat transfer medium. They are potentially cost effective for electric power generation and industrial process heat, but are limited to a maximum temperature of approximately 600°C (1112°F) because nitrate salts irreversibly decompose above that temperature. However, a market exists for industrial process heat applications, and a large market potential exists for fuels and chemicals production requiring heat at temperatures above 600°C. To achieve that high an operating temperature, long-term research is necessary to develop central receiver systems that use either liquid metals, liquid glass, or molten salts that can withstand high temperatures. Candidate materials are hydroxides, carbonates, chlorides, or a gas that can pass through a receiver.

Previous work has shown that systems using liquids as the receiver fluid and the same liquid as a sensible heat storage medium have the potential to deliver heat at high temperatures to a process medium at costs lower than other proposed systems. This work also has resulted in the generation of a direct absorption cavity receiver concept, shown by initial analyses to be more efficient and more economical to manufacture than other high-temperature receiver concepts.

In FY 1982, previously proposed high-temperature central receiver systems that heat air directly in the receiver were analyzed. The analysis shows that delivered energy costs are considerably higher than for heat from a molten nitrate salt system operating at a lower temperature. Electricity produced by these high-temperature air receivers was estimated to cost at least 50% more than for electricity from a nitrate salt receiver despite the higher efficiency of the engine. The principal cause for the high cost is the increased size of the air receiver, which operates at considerably lower thermal efficiency than a molten nitrate salt receiver due to the low heat transfer coefficient of air.

In order to circumvent the problems encountered with a receiver using a gaseous fluid, it may be necessary to utilize a high-temperature liquid receiver. During FY 1983, SERI will continue to develop this high-temperature receiver concept by analyzing the thermal performance of the direct absorption cavity receiver concept.

## 2. Innovative Concentrators

Investigation of two innovative, high-risk collector concepts, having the potential to dramatically reduce heliostat costs, were investigated at SERI in FY 1982. Polymer enclosed (or domed) heliostats were studied via a systems analysis and comparison with glass/metal heliostats. A stretched membrane concept where a thin metallic or polymer film forms the collector reflective surface when stretched on a support frame was also investigated.

a. Polymer Enclosed Heliostats. The polymer-enclosed heliostat system studies encompassed reviewing prior work, updating prior costing estimates, developing an economic comparison methodology, investigating dome support options other than air pressure, screening currently available polymers, and modifying current system performance comparisons. The baseline system description and assumptions used in the analysis are the following:<sup>11</sup>

- (1) A 30-MWt process heat system was selected as the application.
- (2) The delivered cost of energy (1982 dollars per GJ) was determined on the basis of annual required revenue and used as the relative figure of merit.
- (3) Optical degradation with time and losses from thermal piping and transport were not considered.
- (4) The optical performance and cost of a Kynar enclosure and an FEK-244 reflective surface were assumed.

The study reveals that polymer enclosures and reflectors have the potential to dramatically reduce the estimated cost of delivered energy from systems using second-generation heliostats. As shown in Table 6-2, savings of up to 40% could be achieved if expected results from current polymer materials research are obtained. Material requirements and research issues being addressed are associated with both the enclosure and the enclosed reflector. Enclosure materials research in FY 1983 will emphasize enhanced mechanical strength and lifetime, better specular transmittance, lower surface reflectance, and anti-soiling characteristics. Reflector material efforts will pursue enhanced specular reflectance of metalized polymers, and both mechanical and environmental durability.

Other significant findings of the study include the following points:

- (1) After attaining an enclosure life of five years or more, improvements in material optical performance have a much greater impact on delivered energy costs than further increases in material

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<sup>11</sup>Murphy, L. M., A System Study of the Polymer/Enclosed Heliostat Concept and a Comparison with Glass/Metal Heliostats, Solar Energy Research Institute, SERI/SP-253-1791, October 1982.

Table 6-2. Sensitivity of the Predicted Delivered Energy Cost to Various Cost and Performance Modifications (1982 Dollars)

Description				Cost of Delivered Energy for a Given Dome Life, N <sup>(a)</sup>			
Reflector Surface	Enclosure	Collector Cost, \$/m <sup>2</sup>	$\rho\tau^2$ <sup>(b)</sup>	N=1 \$/GJ	N=5 \$/GJ	N=10 \$/GJ	N=20 \$/GJ
FEK-244	Current Kynar	59	0.56	18.0	13.3	12.7	12.4
Specular Aluminum	Current Kynar	59	0.63	15.7	11.6	11.1	10.8
Specular <sup>(c)</sup> Aluminum, Unfocused	Current Kynar	59	0.63	21.6	16.0	15.3	14.9
Specular Silver	Current Kynar	59	0.70	14.1	10.4	10.0	9.7
Specular Silver	Specular Kynar	59	0.77	12.6	9.4	9.0	8.8
Specular Silver	Specular and Anti- Reflective Kynar	59	0.86	11.2	8.31	7.93	7.76
Specular Silver	Specular and Anti- Reflective Kynar	30	0.85	9.02	6.11	5.73	5.56
Second-Generation Heliostat <sup>(d)</sup>		116					10.25

<sup>a</sup>N = number of years (dome lifetime).

<sup>b</sup> $\rho\tau^2$  = effective reflectivity of enclosed heliostat.

<sup>c</sup>All other cases assume "perfect" focusing.

<sup>d</sup>For comparison.

lifetime (Figure 6-2). Realistic discount rates greatly attenuate the effect of capital costs for enclosures as their lifetime increases.

- (2) If a twenty-year dome life represents 100% of the economic potential attainable with extended enclosure life, then a ten-, five-, and two-year enclosure life would represent 95, 84, and 53%, respectively, of the attainable economic potential, using system definition and economic parameters as a baseline.
- (3) Optical degradation was not considered in these studies. The magnitude of degradation is unknown, but it could be important and might impact the delivered energy costs significantly. In addition, methods for effectively cleaning the three optical surfaces (versus one surface for the glass/metal concept) may have to be investigated.
- (4) Focusing of the membrane reflector is an important requirement. For the baseline system selected, delivered energy costs can increase by more than 40% for an unfocused system compared to a focused system. The adequacy of gravity-induced focusing has not been demonstrated.

b. Stretched Membrane Reflector. The research and development effort in FY 1982 on stretched membranes for use as heliostat reflective surfaces emphasized a combination of design, engineering, cost and performance analyses, and testing. Study areas included structural design aspects of stretched membranes and support structures, including analysis of linear and nonlinear deformation, buckling of the support frame, thermal mismatch considerations, focusing effects, wind spillage effects, and the optimal strength and sizing of the membrane support structure. Cost studies of several stretched membrane concepts were also performed. Researchers designed and fabricated a number of bench-scale and field-scale hardware elements, including two 2-m-diameter prototype concentrators (Figure 6-3); a potentially low-cost 2-axis tracking support base (Figure 6-3); seven 1-m-diameter stretched membrane reflective modules of various designs, which were tested for optical accuracy using a laser ray trace instrument test bed; and a prototype 3-m-diameter reflector based on a commercial trampoline. A number of mechanisms for attaching membranes to support structures appropriate for either low or high production levels were tested, and seven candidate metalized polymers were screened as potential reflective surfaces for stretched membrane heliostats and other innovative concentrators.

Major findings of this work are described below:

- (1) Based on both analysis and testing of small-scale models, the stretched membrane concept appears capable of providing high optical quality surfaces (approximately 2.0 rms surface errors). The stretching process tends to smooth out imperfections, and initial surface distortions and edge distortions emanating from the support frame are effectively attenuated.

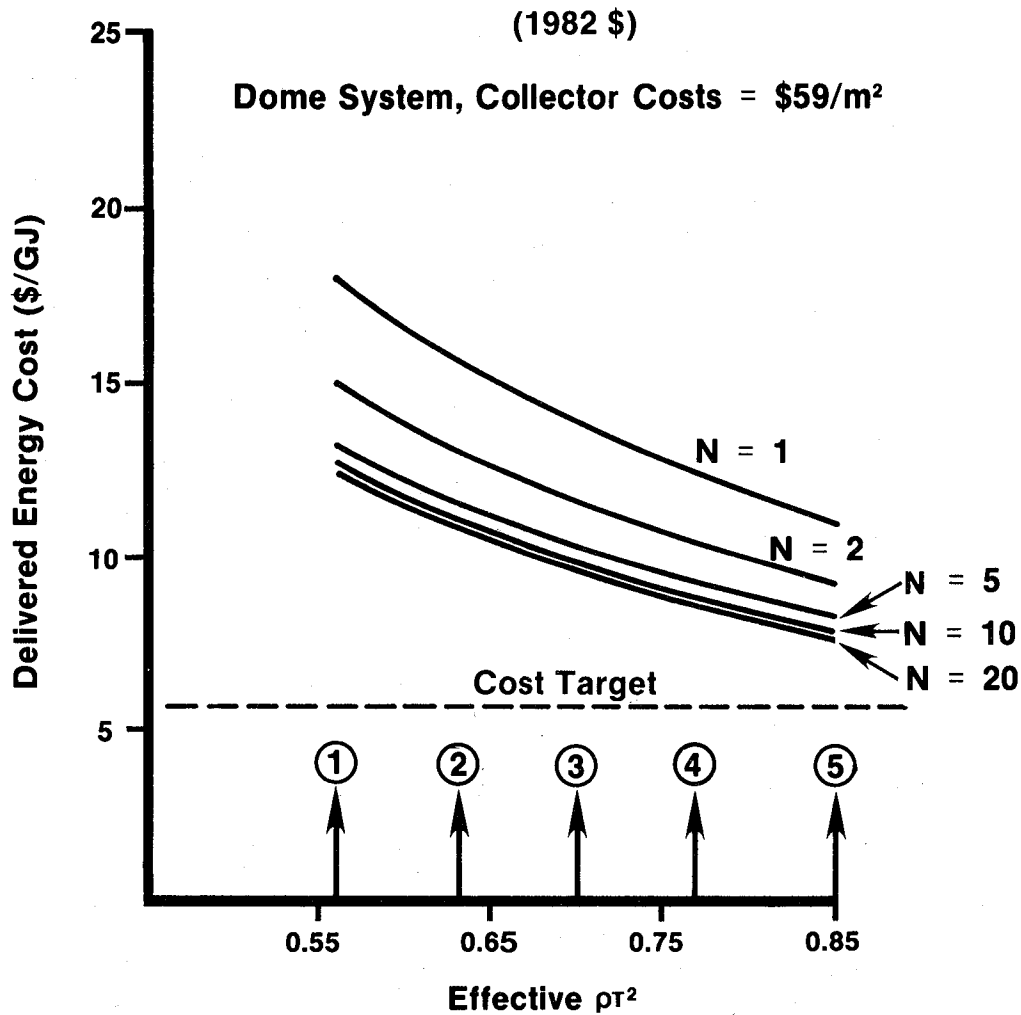


Figure 6-2. Delivered Energy Cost Versus Effective  $\rho\tau^2$  for Several Values of Dome Lifetime ( $N$ ) (Collector Cost = 59\$/m²) Notes: (a) Baseline FEK reflector,  $\rho\tau^2 = 0.56$ ; (b) Replace FEK with specular aluminum,  $\rho\tau^2 = 0.63$ ; (c) Replace FEK with specular silver,  $\rho\tau^2 = 0.70$ ; (d) Replace FEK with specular silver and make Kynar perfectly specular; (e) Replace FEK with specular silver, make Kynar perfectly specular, and make Kynar with perfectly anti-reflective properties.

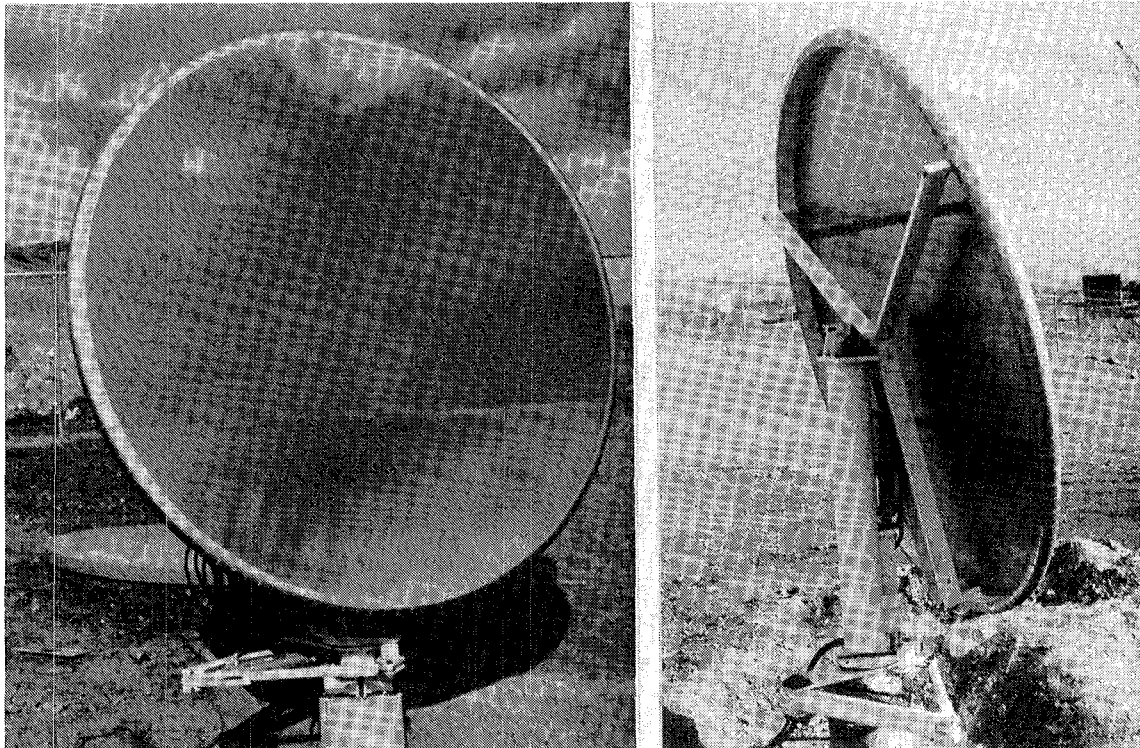


Figure 6-3. Stretched Membrane Collector Concept Designed and Fabricated at SERI

- (2) Lightweight yet durable reflector and support structures appear attainable with this concept. When a metalized polymer reflector surface laminated to the main tension membrane is used instead of glass, heliostat weights on the order of  $10 \text{ kg/m}^2$  ( $2 \text{ lb/ft}^2$ ) appear feasible -- as opposed to  $41 \text{ kg/m}^2$  ( $8 \text{ lb/ft}^2$ ) for current second-generation heliostats.
- (3) Attachment of the membrane to the support frame in the most cost-effective manner depends on the size of the structure and manufacturing techniques available as well as the number of systems being manufactured. However, several mechanical, bonding, and welding procedures have been identified that appear quite amenable to the level of edge loading required.
- (4) The cost of the reflector, frame, and support structure (including drive attachment) for this concept is estimated to be  $25\$/\text{m}^2$  ( $2.5\$/\text{ft}^2$ ). The cost/performance benefits result primarily from the reduced weight.
- (5) For most expected wind velocities, the effect of wind loading will be minimal.
- (6) Focusing will be required for optimum optical cost/performance of the stretched membrane concept. At least two potentially acceptable means of focusing have been identified: the common



vacuum approach and an innovative laminated membrane concept that allows variable focusing.

- (7) The required membrane tension appears amenable to the use of polymeric materials for the main tension membrane. Use of other high-strength composites for the frame and support structure may further reduce weight.
- (8) Although the stretched membrane reflector and the required support structure represent only a portion of the total collector system, it is significant because it represents approximately 45% of current heliostat costs and up to 85% of total heliostat mass (excluding foundation).

A number of uncertainties exist that must be clarified before the full potential of the membrane heliostat can be assessed: the availability of suitable high-strength polymeric membrane materials, the advantages of polymeric membranes over metallic membranes, and the annual energy performance of the systems. The most important mechanical/structural design issues that must be studied include (1) establishment of practical limits for further weight reduction, (2) establishment of more precise buckling criteria for both local and gross stability as a function of heliostat size and design tension, (3) enhancement of the buckling resistance of thin tubular structures, (4) snap through of laminated curved membrane reflectors, and (5) aerodynamic load reduction schemes for the reflector assembly.

### 3. Thermal Storage

Some degree of energy storage is required in any solar energy system because of the intermittent nature of the solar resource. Sensible or latent heat thermal storage is the most natural and cost-effective mode of storage for solar thermal systems. Since 1978, SERI has been evaluating thermal storage concepts under funding from the Department of Energy, Energy Storage Technology Division. The approach has been to develop a methodology to determine the value of thermal storage for a solar thermal system (depending on the capacity and duration of the storage) and estimate the cost. Storage concepts with value-to-cost ratios greater than 1 (unity) are then subjected to research to determine technical feasibility.

During FY 1982, a value-to-cost analysis was completed of a large number of advanced storage concepts having storage temperatures ranging from the currently attainable value of 385°C (725°F) to a value of 1450°C (2642°F) yet to be attained. Some of these items, for which preliminary (prior to FY 1982) cost estimates produced value-to-cost ratios greater than 1, were selected for research (Table 6-3.) In some cases, the final cost projections are considerably higher than the original projections, resulting in investigation of systems that have value-to-cost ratios below 1.

The technical feasibility of the five storage systems listed in Table 6-3 was investigated during FY 1982. Analysis, conceptual design, and experimental work were conducted for a high-temperature (1400°C, 2552°F) thermal storage

Table 6-3. Value-to-Cost Ratios for Advanced Thermal Storage Concepts with Appropriate Advanced Central Receivers

Storage Technology	Storage Capacity, hours	Application	Value, \$/kWt-h	Cost, \$/kWt-h	Value/Cost Ratio
Molten Slag	6	Electric power	20-25	28	0.7-0.9
High-Temperature Molten Salt	6	Electric power	25	5.0	5
Draw Salt/Air Rock <sup>(a)</sup>	48	Process heat	10-20	6.7	1.5-3.0
Phase-Change Salt/Ceramic Pellets	1-15	Process heat	20	25-30	0.7-0.8
Metal/Phase-Change Salt	1-15	Process heat	20	10	2

<sup>a</sup>With direct-contact heat exchanger.

system for a 23-MWt solar energy plant using molten glass as the storage and heat transfer media, a central receiver, and a 10-MWe Brayton-cycle turbine. Key issues in advanced high-temperature molten salt thermal storage were investigated. Systems analyses have shown that high-temperature (800 to 1100°C, 1472 to 2012°F) molten salts are potentially attractive both as receiver coolants and as storage media, but at high temperatures they may require direct contact heat exchange, new kinds of storage tank insulation, and new ways to maintain a sharp thermocline. Research was initiated in 1982 on molten nitrate salt storage at 550°C (1022°F) in combination with air-to-rock storage where the heat is transferred from the molten salt to the rock using an air loop. Applications of this technology are for industrial process heat. The work involves evaluation of the heat transfer coefficient between the molten salt and air in a packed column heat exchanger. An experimental loop was constructed to develop methods for predicting the performance of direct contact heat exchangers and to test various packing designs. These tests are planned for FY 1983.

Experimental and analytical investigations were made by the Institute of Gas Technology for energy storage in conjunction with solar central receiver systems using air as a working medium and a Brayton energy conversion cycle operating at 700 to 900°C (1292 to 1652°F) for electric power generation. Energy storage is achieved by direct contact heat exchange between air and

pellets of high heat capacity consisting of a mixture of phase-change salts within a porous ceramic matrix. The salt changes phase from solid to liquid over the storage operating temperature range. The molten salt is held within the void space in the ceramic body primarily by capillary forces. A laboratory-scale direct contact heat exchanger was used to evaluate the performance of a randomly packed bed of pellets. An economic analysis showed that for six hours or less storage capacity, the value-to-cost ratio would exceed 1 (unity). Storage units having this capacity would also cost less than thermal storage in ceramic bricks. Analysis was initiated on a concept employing hot salt storage for a solar central receiver system using water and steam as the heat transfer medium.

The most promising storage concept appears to be the use of high-temperature molten salts as both the sensible heat storage medium and the working fluid in a central receiver system. Research in FY 1983 will concentrate on further development of this advanced concept.

### C. FUELS AND CHEMICALS

Prior to FY 1982, efforts to employ solar thermal energy for the production of fuels and chemicals have been devoted to determining the utility and applicability of solar thermal energy to primary fuel and chemical processes. Results of exploratory studies demonstrated that this energy resource could be used to drive all major fuel and chemical conversion processes, including reduction, gasification, pyrolysis, and liquifaction. In addition, it was clear that intermittent, high-flux, high-temperature inputs could be accommodated within a broad range of processes. Other work with windowed reactors and moving beds demonstrated ease of control over heat and mass transfer using direct radiant heat transfer to solids.

Building upon this exploratory research base, FY 1982 activities focused on analytical and experimental tasks that would provide:

- (1) Insight and understanding into whether the solar thermal resource contained unique or advantageous elements that could be beneficial to the fuel and chemical industry,
- (2) Identification and definition of the technical barriers that would limit or prevent utilization of the resource, and
- (3) Development of a program and management structure that would result in assessing the technical and economic feasibility for production of fuels and chemicals from renewable resources.

FY 1982 program accomplishments are described below:

#### 1. Analyses

##### a. Determination of Utility of Solar Thermal Energy Resource.

Investigations were directed at determining whether the solar thermal resource offered any unique or advantageous elements that could be beneficial to the

fuel or chemical industry. This work has demonstrated the technical value of high-temperature flux and heating rates for specific reactions. There is the potential for high thermodynamic efficiencies, with high Carnot efficiencies at the higher temperatures. It was also ascertained that a wide choice of chemical systems could make use of these efficiencies and that both fuels and chemicals could be produced from a large variety of feedstocks. One potentially powerful element of the solar thermal resource is the excellent matching of solar receiver technology since heat can be supplied by the solar receiver at temperatures and amounts dictated by the chemical process. This advantage could result in reduced internal heat transfer and efficient use of materials and heat and this would also permit chemical reactions to absorb much larger amounts of energy per unit weight and volume than IPH or electrical generation systems.

Although less developed, the provision of carbon-free selective or controlled exposure appears to provide process conditions that result in rapid reaction rates and product yields. Promising, unique photon-driven processes require more evaluation before their potential can be estimated. Qualitatively, the resource is clean, renewable, and environmentally acceptable. Economically, preliminary assessments indicate favorable long-term cost trends in relation to fossil resources.

b. Determination of Technical Barriers. An assessment was performed to identify the technical barriers that prevented industry from capitalizing on the potential for solar thermal derived fuels and chemicals. It was learned that, in essence, while specific solar capability exists (i.e., high-temperature capability), the technical base to make use of it has not been developed. Specifically, high-temperature chemical reactor technology is unknown under conditions of solar transients. This area requires a new understanding of materials and reactor design under conditions of multiple, deep thermal cycles. This work needs to be extended to include investigating reactor and catalyst behavior under thermal cycling. It also requires new methods to control reaction time under conditions of variable heat input. The assessment also indicated that process control and stability are unknown for integrated solar plants. This aspect requires knowledge of how to quickly adapt chemical operations to large thermal transients (swings) as well as understanding the dynamics of processes with variable heat flow and product stream flow. New methods will have to be developed for rapid start-up, shutdown, and plant operation.

In performing this technical assessment, several major fuel and chemical processes were examined in great detail. What was learned is that there is a great deal of commonality in terms of missing technologies among the processes. These have been identified as "core technologies." A program structure has been developed to focus on these technologies because an appraisal of the technical feasibility of the core technologies will permit applications to a range of fuel and chemical processes. The goal is to provide the basic fuel elements ( $H_2$  and  $CO$ ). The selected mechanism or process to focus the effort is thermochemical hydrogen.

## 2. Experimental Research

The following experimental work was conducted to initially assess the major technical issues confronting the program:

- (1) Lawrence Livermore National Laboratory completed the White Sands Solar Furnace Tests on the "Decomposition of Zinc Sulfate." This research work examines the value of direct flux on reaction rates. Disassociation started at 849°C (1560°F) and operated best at 1099°C (2010°F). While valuable data were obtained, deficiencies were noted in materials handling and instrumentation for obtaining high-temperature data.
- (2) Lawrence Berkeley Laboratory conducted tests at the Advanced Component Test Facility on the "Small Particle Heat Exchanger." The engineering prototype explored unique methods to transfer solar heat to gases. The technique was so successful that the receiver walls remained substantially cooler than the gas output temperature.
- (3) General Atomics Technologies completed design and assembly of the "Gaseous Catalytic Reactor." The effort will lead to a fundamental understanding of the design limits of metallic reactors. Additional understanding of catalyst stability, reactor performance, heat and mass transfer, and operating procedures will be obtained.
- (4) Efforts on "Continuous Direct Radiant Pyrolysis" were initiated at Princeton University. The bench-level work explores the fundamentals of direct radiant pyrolyzation of feedstocks within a fluidized reactor. This effort will address the physical phenomena such as optimal particle/flux densities and kinetics. An arc-image furnace used for flash pyrolysis of biomass is shown in Figure 6-4.
- (5) SERI initiated an effort to investigate the scientific potential for photon-driven reactions. The work will focus on both flat plate and concentrating systems. Photothermal hybrid systems will be assessed. The work will result in a research plan to provide programmatic direction.
- (6) The University of New Hampshire carried out bench-level experiments on "High-Temperature Heat Transfer." This gas recirculation solar hybrid technique was used to investigate the gasification of carbonaceous materials (Figure 6-5). These tests will provide fundamental heat transfer data. The program offers promise in the reduction of feedstock utilization and plant cost.

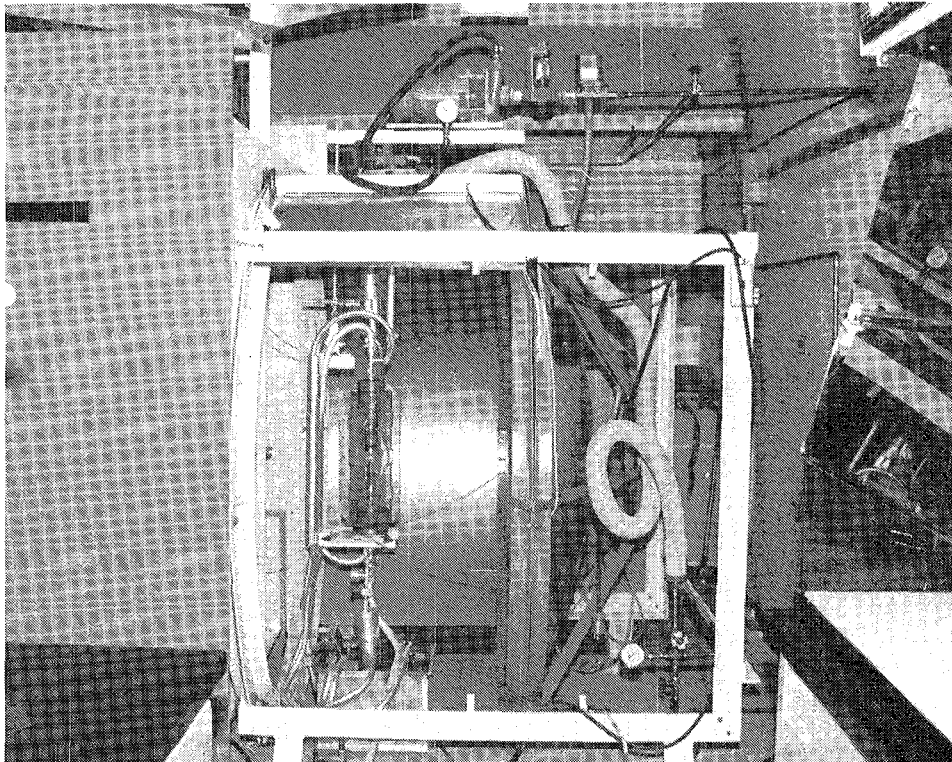


Figure 6-4. Arc-Image Furnace for Flash Pyrolysis of Biomass

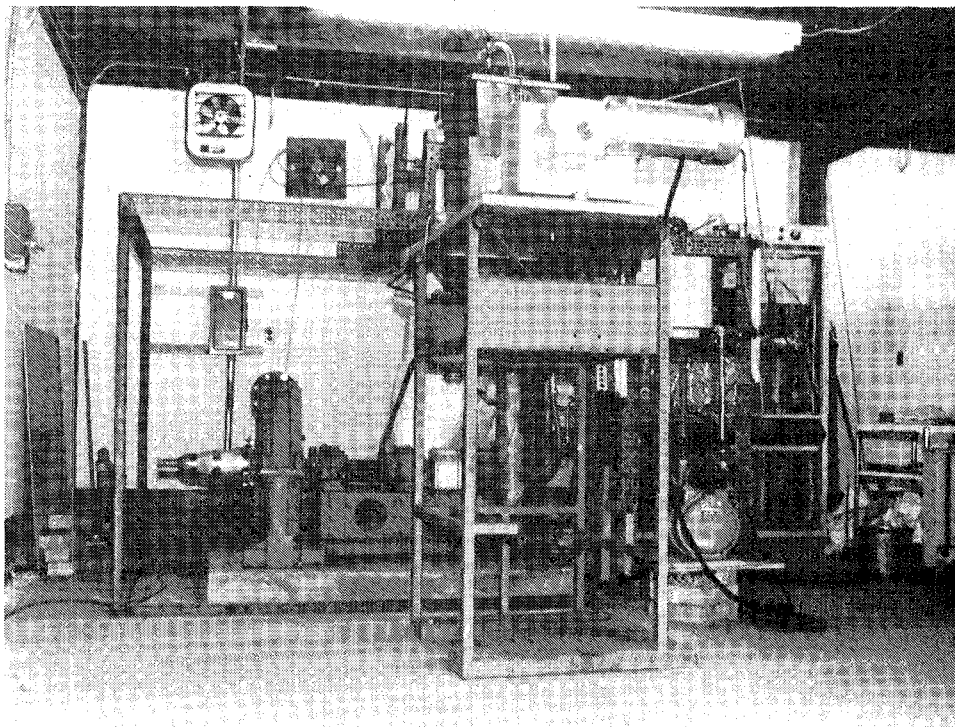


Figure 6-5. Coal Gasification Reactors in Laboratory Control Area

#### D. ADVANCED RESEARCH PROGRAM

The Solar Thermal Advanced Research Program was established to foster innovative ideas and concepts through cooperative participation by researchers in universities and industry to achieve the long-term goal of cost competitiveness of solar thermal systems and components. Basic research consisting of experiments in laboratories and test facilities, analysis of critical problems, and development of innovative concepts are conducted within established priorities. During FY 1982, this activity encompassed research projects at two universities, the Georgia Institute of Technology and the University of Houston, and preparation of an innovative research PRDA (Program Research and Development Announcement) to be issued in early FY 1983.

##### 1. University of Houston

The University of Houston has provided 10 years of continuous research support to the solar thermal program. Areas of special interest are central receiver analysis and assessment, optical materials and photo degradation, radiation heat transfer, advanced and chemical energy storage and transport, and photo and thermochemical research based on unlimited renewable feedstocks. Progress and accomplishments in these areas of research during FY 1982 are described in the following paragraphs.

a. Cyclic Catalytic Converter. The feasibility of transmitting high solar flux from the outside of a central receiver to the inside of a catalytic bed using sodium heat pipes is being evaluated. A pilot development unit using a single heat pipe operating at about 850°C (1562°F) was designed, and fabrication of parts initiated. An energy input of 20 kWt will drive the  $\text{CH}_4\text{H}_2\text{O}$  reforming reaction as a potential carrier for a chemical energy transmission system. The unit is designed to process up to 100 SCFH of  $\text{CH}_4$  using an industrial catalyst. Computer control, data acquisition, and data analysis will provide realistic simulation of the solar environment. The pilot development unit will be used to verify model predictions, provide accurate parameters, and check catalysts for deactivation under cyclic conditions.

b. Solar Degradation. In FY 1982, a detailed study was initiated to research the optical, structural, and compositional degradation of solar energy materials (e.g., absorber coatings, reflector stacks, and structural materials) under concentrated solar radiation. Conclusive experimental evidence that photo effects play significant beneficial and detrimental roles in defining the long-term stability at operating temperatures of various solar materials was obtained. Photo enhanced stability due to photodesorption of oxygen-bearing species from the surface of materials has been shown to occur in black chrome and black cobalt absorber coatings and in chromium. Photo reduced stability (photo corrosion) in the form of enhanced oxidation occurred in iron exposed to water vapor and oxygen. Further studies of photo effects will be conducted in FY 1983 for other relevant materials with an emphasis on ceramics.

c. Thermochemical Storage Cycles. The decomposition of ammonium hydrogen sulfate (AHS) is a promising concept for chemical storage of solar energy. Prior work has shown that, as in most water splitting reactions, the limiting step is the decomposition of  $\text{ZnSO}_4$ . A thermogravimetric kinetic study shows that solid  $\text{ZnSO}_4$  decomposes to  $\text{ZnO} \cdot 2\text{ZnSO}_4$ , which in turn decomposes at a slower rate to  $\text{ZnO}$ . The decomposition of the zinc sulfate product from the AHS cycle resembles that of  $\text{ZnO} \cdot 2\text{ZnSO}_4$  although some discrepancies exist. An  $\text{SO}_3/\text{SO}_2$  analysis of product gases was developed based on titration of the trapped gases in  $\text{NaOH}$  solutions. Using this analysis, the decomposition of  $\text{ZnSO}_4$  was studied in a flow system in the temperature range of 840 to 950°C (1544 to 1742°F). Principally,  $\text{SO}_3$  comes off during the initial portion of the reaction (35 to 55% yield) followed by  $\text{SO}_2 + 1/2 \text{O}_2$  (45 to 65% yield). The decomposition of  $\text{ZnSO}_4$  in a  $\text{NaCl}$  melt gives reaction products in addition to  $\text{SO}_3/\text{SO}_2$  and is, therefore, not suitable for an energy storage cycle. The decomposition can be carried out in a  $\text{Li}_2\text{SO}_4$  melt utilizing a  $\text{V}_2\text{O}_5$  catalyst. Suitability of this and similar processes will be verified experimentally in FY 1983.

## 2. Georgia Institute of Technology

The Advanced Research Program at the Georgia Institute of Technology is directed toward providing a technical base for the use of concentrated solar energy for the production of high temperatures to ultimately increase conversion efficiencies of thermodynamic cycles and to produce fuels and chemicals. The Georgia Tech research program addresses the following requirements of high-temperature solar energy conversion:

- (1) Functional and durable materials for high temperature receivers, reactors, and energy conversion systems
- (2) Design integration of materials and optical requirements for solar thermal receivers
- (3) Basic engineering data on the use of direct, high solar flux for the production of fuels, chemicals, and high-temperature process heat
- (4) Improved high surface temperature diagnostic techniques

a. Direct Flux Entrainment Reactor. A single pass, entrainment type reactor (Figure 6-6) was designed, built, and initially tested at the Georgia Tech Advanced Components Test Facility (ACTF). In this concept, a finely ground particulate is entrained in a gaseous flow and exposed to intense solar flux. The particulate acts as an absorbing medium, reaches reacting temperature, and chemically combines with the surrounding gas to form intermediate and final products. Initial testing of the reactor at the ACTF confirmed the proper operation of the reactor and associated hardware in the solar beam and demonstrated efficient entrainment of inert particles for a variety of solar flux and flow conditions.



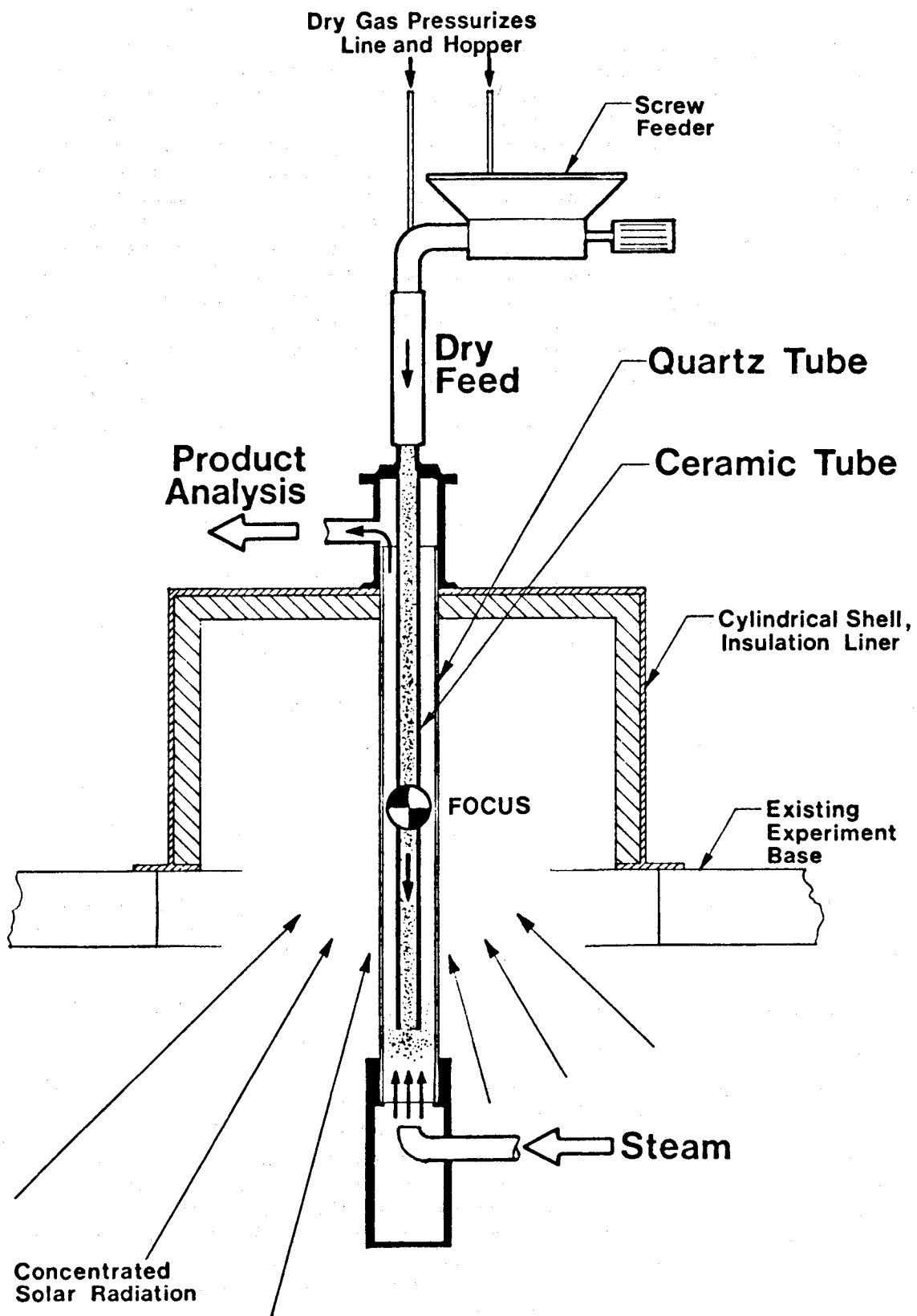


Figure 6-6. Georgia Tech Entrainment Reactor

b. High-Temperature Window Materials. Transparent and translucent materials were surveyed to determine their suitability for use in a high-temperature, chemically reactive environment (fused quartz, Vycor, Pyrex, single-crystal sapphire, Vistal, magnesium-aluminum spinel, and Kodak Itrans 1, 3, and 5) were tested at the ACTF at incident fluxes up to 200 W/cm<sup>2</sup>. The test program included measurement of solar transmission and equilibrium operating temperatures with and without an optical cavity and qualitative observation of thermal shock during solar exposures up to 1 hour. Test results obtained during FY 1982 show that transparent materials are generally superior to translucent materials for this application although the latter show a potential for better chemical and erosion resistance and are less costly.

c. Ceramic Materials. A test receiver was designed and fabricated to provide controlled exposure of ceramic materials to intense solar flux and selected chemical atmospheres. This receiver is a well-insulated, downward-facing cavity with provisions for injecting purge and test gases and for measuring temperatures on 8-in.-diameter cylindrical and flat-plate test specimens. Sustained cavity temperatures of 1260°C (2300°F) were achieved in a test program at the ACTF; a variety of ceramic materials have shown premature degradation under direct solar flux. Microstructural and chemical analyses of the test specimens will be conducted in FY 1983 to determine failure modes.

d. Materials Modeling. A thermal analysis computer model was developed to predict surface and interior temperatures in windows and opaque ceramic materials exposed to direct solar flux. The model will be used to predict thermal stress failure in various materials and shapes exposed to a high-temperature environment in solar receivers. A simplified model was used to predict temperature profiles in transparent materials and preliminary comparison was made with measurements from the ACTF window test program.

e. Surface Temperature Diagnostics in a High Solar Flux Environment. Common methods of measuring temperatures, reflectivities, emissivities, and related properties of material surfaces encounter serious difficulties when applied to the high flux environment of a concentrated solar beam. Research and development of a noncontact surface temperature diagnostic technique that can accurately measure surface temperatures in operating high-temperature receivers was initiated in FY 1982.

### 3. Innovative Research Program

The Innovative Research Program sponsors research of critical problems and issues in solar thermal technology and develops innovative concepts designed to speed implementation of the technology. The program develops innovative solutions that will lead to quantum improvements in performance, cost, or application of solar thermal systems. The program is conducted through sequential phases consisting of (1) concept development, in which innovative concepts will be identified and evaluated, and (2) advanced

development, in which those ideas and approaches showing promise during the concept development phase will be examined in detail.

A PRDA (Program Research and Development Announcement), by which multiple awards are planned, was prepared in FY 1982. The PRDA will be issued in the first quarter of FY 1983 and will solicit proposals from the research community for the first phase of the program. The solicitation seeks new and advanced ideas applied to materials research, thermal and chemical science, and engineering development in support of solar thermal research goals. During FY 1983, proposals in response to the PRDA will be evaluated and contract awards made.

## SECTION VII

### PLANNING AND ASSESSMENT

#### A. TECHNOLOGY ASSESSMENT

The objectives of the technology assessment task are (1) to determine and recommend internally consistent energy and system-level cost and performance targets for solar thermal technology based on market value and (2) to identify options and recommend priorities for the Solar Thermal Advanced R&D Program and other solar thermal subprogram plans.

The effort centered around an inter-laboratory Solar Thermal Cost Goals Committee (STCGC), which periodically met to review and critique progress of ongoing work. Results of the analyses and final recommendations of the committee were presented to DOE management in February 1982. This work culminated in general and specific implications for solar thermal research and development.

##### (1) General Implications for R&D

- (a) Cost and performance goals should be used both to target and to measure R&D progress.
- (b) Progress toward performance goals is easier to verify than progress toward cost goals.
- (c) A finer level of goals delineation is required to target R&D efforts.
- (d) Regular assessment of progress toward goals is necessary.
- (e) If progress is not adequate, redirection is required.

##### (2) Specific Implications for R&D

- (a) Significant reductions in concentrator cost will enhance the ability to compete with fossil systems.
- (b) Reducing concentrator cost will require technological advances beyond second-generation heliostats (and other concentrators).
- (c) These concentrator goals could be supplanted by increased systems efficiency goals, which would require R&D of transport, storage, or heat engines.
- (d) Goals for a solar thermal fuels and chemicals subprogram should be focused on output-chemical/energy-type if the process is unique to solar technology.

## B. SOLAR THERMAL BENEFITS ANALYSIS

During FY 1982, solar thermal technology benefits assessment was carried out.<sup>12</sup> This analysis assessed the benefits of replacing conventional fuels with solar thermal systems with different fuel price scenarios and levels of solar thermal market penetration.

The future energy cost savings associated with the development of cost-competitive solar thermal systems were estimated in this assessment. The analysis was restricted to electric applications for 15 high-insolation/high-energy-price locations. Three fuel price scenarios and three 1990 system costs were considered, reflecting uncertainty over future fuel prices and solar thermal cost projections.

Solar thermal technology R&D was found to be unacceptably risky for private industry in the absence of federal support. Energy cost savings were projected to range from \$0 to 10 billion (Table 7-1), depending on the system cost and fuel price scenario assumed. The normal risks associated with investments in R&D were accentuated because the Organization of Petroleum Exporting Countries (OPEC) cartel can artificially manipulate oil prices and undercut the growth of alternative energy sources. When this fact was weighed against the potential benefits of developing cost-competitive solar thermal systems, federal participation in their R&D was found to be in the national interest.

Analysis was also made of two federal incentives, both currently in use: the Federal Business Energy Tax Credit and direct R&D funding. These mechanisms can be expected to provide a significant portion of the required incentives to establish a viable self-sustaining private solar thermal industry.

## C. ASSESSMENT OF BOWL CONCEPT

The Technology Program Integrator Office completed a Congressionally mandated technology assessment of the hemispherical bowl concept and provided DOE a recommendation for future action on the Crosbyton project (described in Section V.A). The assessment appraised the status of bowl component and system technology, its performance, and cost potential. It concluded that the technology concept had been demonstrated by the construction and operation of the Analog Design Verification System (65-ft prototype bowl), but that a number of significant issues remain unresolved. The most important of these is the cost-effectiveness of bowl technology compared to other solar thermal technologies.

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<sup>12</sup>Gates, W. R., "Solar Thermal Technology Development: Energy Cost Savings, Environmental and Petroleum Import Impacts, and the Implications for Federal Participation," Jet Propulsion Laboratory, Pasadena, California, February 1983.

Table 7-1. Total Net Energy Cost Savings of Solar Thermal Electric Systems  
(1990 Values in Billions of 1981 Dollars)

Solar Thermal System Costs, <sup>(b)</sup> \$/kWe	NEP-III Energy Price Scenario <sup>(a)</sup>		
	Low	Medium	High <sup>(c)</sup>
2200	0	0	1
1750	0	(d)	3
1300	(d)	2	10

<sup>a</sup>Low, medium, and high refer to the NEP-III (National Energy Plan) scenarios based upon the 1990 imported oil price of 44, 52, and 68 (1981 dollars per barrel).

<sup>b</sup>Low, medium, and high system costs reflect varying production volumes and levels of R&D success.

<sup>c</sup>Assumes that conventional generating capacity represents the best alternative technology. This assumption may prove unrealistic, especially in the high oil price scenario.

<sup>d</sup>Positive values that become zero after rounding to nearest billion.

#### D. FOAM GLASS APPRAISAL

A preliminary study to investigate the potential use of foam cellular glass as a reflective surface substrate in solar thermal systems was completed. A summary of the study results follow:

- (1) Foam glass allows construction of a stiff, lightweight structure with a coefficient of thermal expansion equal to that of mirrored glass and with superior optical performance over the operating temperature range.
- (2) In solar thermal applications, cellular glass must be sealed to avoid water contamination, which will cause severe degradation during freeze/thaw conditions.
- (3) Economic uncertainties regarding foam glass are high because the material is not being produced on a continuous basis.

A further review of this issue will be conducted in FY 1983.

#### E. RETURNS FROM INVESTMENTS IN SOLAR THERMAL ENERGY

A study of investors and federal treasury returns from investing in solar thermal energy systems was undertaken in FY 1982. Federal treasury investment consists of tax credits, depreciation deductions, and -- for solar thermal systems -- a business energy tax credit for non-utility owners. The study described the probable returns to the federal government as well as to third party investors from investing in the first commercial central receiver plants. The returns to the federal government were narrowly defined as tax flows to and from the solar plant and did not include taxes paid by plant personnel, manufacturers, or employees needed to produce plant equipment or to construct the plant.

The final report of the study<sup>13</sup> concluded that the federal government lowers the risk to solar thermal investors, which also increases the return on the investors' equity, by providing the business energy tax credit. By continuing to provide this credit to third-party owners of the initial high-cost solar thermal systems, the government will allow these investors a higher expected return than will be realized by investors in future low-cost systems. Given the assumptions used in the study and a continuing business energy investment credit, initial high-cost systems can provide expected returns that will encourage venture capital investors. Furthermore, returns to the federal government via the energy tax credit are almost always above zero and have the potential of providing the treasury with a solid future revenue source. Returns for future low-cost systems should be sufficient without a direct energy tax credit.

#### F. 10-MWe PILOT PLANT COST ANALYSIS

An analysis assessing the accuracy of cost estimates for the 10-MWe Central Receiver Pilot Plant<sup>14</sup> located near Barstow, California, was conducted. The approach taken was to prepare a history of the pilot plant cost estimates, which was then compared to cost estimate histories of other first-of-a-kind energy process plants. Based upon these comparisons, the pilot plant estimates have been remarkably accurate.

Cost estimates for the pilot plant were developed prior to and throughout the course of the project. It should be noted that during this time the original plant sizing objectives remained unchanged: (1) 10-MWe power to the grid from the receiver; (2) approximately 8 hours and 4 hours of 10-MWe operation on the summer and winter solstices, respectively; (3) 28 MWe-h of thermal storage capacity; and (4) 7 MWe power to the grid from thermal storage. Scope

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<sup>13</sup>Sharp, J. K., and Miller, G. J., Investor and Federal Treasury Returns from Investing in Solar Thermal Energy, SAND82-8057, Sandia National Laboratories, Livermore, California, February 1983.

<sup>14</sup>Radosevich, L. G., Accuracy of the Barstow Solar Thermal Pilot Plant Cost Estimates, SAND83-8217, Sandia National Laboratories, Livermore, California, June 1983.

reductions were implemented, however, when the cost estimates exceeded available funding. The major reductions were the deletion of a semi-automatic and automatic control capability and deferral of some start-up testing. Current plans call for these activities to be restored in FY 1983 and 84.

The first pilot plant cost estimate, \$115 million, was developed prior to the completion of conceptual designs and prior to site and utility partner selection. At the present time the total estimated cost is \$140.7/million (\$119.7/million for DOE and \$21.0 million for the project's cosponsors. This cost is 22% higher than the initial estimate. The major factors affecting the increase are (1) unexpectedly lengthy procurement procedures, which caused schedule slips and thereby increased costs due to inflation; (2) higher-than-expected inflation; and (3) fabrication and construction problems for which an insufficient cost contingency existed.

Considering the difficulty in predicting inflation rates over the past few years, the pilot plant cost estimates correlate well with real costs. For example, if annual cost outlays are deflated back to constant 1978 dollars based on an 8% inflation rate, then the real costs of the pilot plant increased only 9% relative to the first cost estimate. Real cost increases, based on 10% and 12% inflation rates, were only 6% and 3%, respectively. Inflation rates from 1978 to 1981 averaged about 10.2%, therefore the pilot plant real costs have increased only slightly.



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## APPENDIX A

### ACRONYMS, ABBREVIATIONS, AND GLOSSARY OF TERMS

#### A. ACRONYMS AND ABBREVIATIONS

ACTF	Advanced Components Test Facility (Georgia Tech)
ADVS	Analog Design Verification System (Crosbyton bowl)
Ag	silver
AGT	advanced gas turbine
AHAC	Active Heating and Cooling (Program)
ALO	DOE Albuquerque Operations Office
ANSI	American National Standards Institute
CLCPSC	cylindrical, line concentrating, pressure stabilized collector
CRTF	Central Receiver Test Facility (Sandia National Laboratories)
Cu	copper
CY	calendar year
DAS	data acquisition system
DCS	distributed collector system
DOE	U.S. Department of Energy
ESOR	experimental solar only receiver manufactured by United Stirling AB
FEK(-244)	an aluminized reflector material manufactured by 3M Company
FMDF	fixed mirror distributed focus (collector)
FY	fiscal year
HAC	heliostat array controller
HTF	heat transfer fluid
ID	inner diameter
IEA	International Energy Agency
IPH	industrial process heat

JPL	Jet Propulsion Laboratory
MISR	Modular Industrial Solar Retrofit (Project)
MIT	Massachusetts Institute of Technology
OD	outer diameter
O&M	operation and maintenance
OPEC	Organization of Petroleum Exporting Countries
ORC	Organic Rankine-cycle (engine)
PCA	power conversion assembly
PDC-1,2	Parabolic Dish Concentrator, Nos. 1 and 2
PDTS	Parabolic Dish Test Site (JPL)
PNL	Pacific Northwest Laboratory
PON	Program Opportunity Notice
PPT	Performance Prototype Trough
PRDA	Program Research and Development Announcement
QTS	qualification test system
R&D	research and development
RH	relative humidity
SABC	subatmospheric Brayton-cycle (engine)
SAGT	solarized advanced gas turbine
SAN	DOE San Francisco Operations Office
SCE	Southern California Edison Company
SCSE	Small Community Solar Experiment
SERI	Solar Energy Research Institute
SMC	sheet molding compound
SNLA	Sandia National Laboratories-Albuquerque
SNLL	Sandia National Laboratories-Livermore
SPPP	solar pond power plant

SRE	subsystem research experiment
SSPS	Small Solar Power Systems (Project)
STCGC	Solar Thermal Cost Goals Committee
STEP	Solar Total Energy Project
TBC	test bed concentrator
TES	thermal energy storage
TRNSYS	a computer simulation program
USAB	United Stirling AB of Sweden
USS	United States Steel
UV	ultraviolet (light)

## B. GLOSSARY OF TERMS

alternator - an electric generator that produces alternating current.

absorber or receiver - a component of a solar collector that collects solar radiation in the form of heat. The heat is transported by a heat transfer fluid through the receiver to its point of use.

absorptance - the ratio of absorbed to incident solar radiation. Absorptivity is the property of a material to absorb radiation.

baseline - reference against which a comparison is made.

baseload electric plant - an electrical generating facility that is designed primarily to satisfy a continuous demand.

Brayton-cycle engine - a heat engine that uses the thermodynamic cycle used in jet (combustion turbine) engines.

Btu - British thermal unit; the amount of heat required to raise the temperature of one pound of water (at 34°F) one degree Fahrenheit.

buffer storage - energy storage that is designed to allow a solar energy system to operate smoothly under transient solar conditions.

bus bar energy cost - the cost of producing electricity including plant capital and operating and maintenance expenses. Does not include cost of transmission or distribution.

cavity receiver - a receiver in the form of a cavity where the solar radiation enters through one or more openings (apertures) and is absorbed on the internal heat absorbing surfaces.

central receiver system - a solar-powered system that uses an array of computer-controlled sun-tracking mirrors (heliostats) to concentrate the available solar radiation and focus it onto a nearby tower-mounted receiver. The energy absorbed by the receiver is removed as thermal energy.

closed-loop system - a system in which no part is vented to the atmosphere.

cogeneration - production of two or more types of energy by the same system, e.g., electricity and process heat.

collector efficiency - the ratio of the energy collection rate of a solar collector to the radiant power intercepted by it under steady-state conditions.

concentrator - a device that concentrates the sun's radiation onto a given area, thereby increasing the intensity of the collected energy.

concentration ratio - ratio of reflected radiant power impinging on a surface divided by the radiant power incident upon the reflecting surface.

convection - heat transfer resulting from fluid motion in the presence of a temperature difference.

distributed receiver system - a solar-powered system in which each concentrating collector has its own attached receiver.

dual-axis tracking ability - the capability of moving independently in two directions, e.g., in both north-south and east-west directions.

endothermic reaction - a chemical reaction that absorbs heat.

evaporator - a heat exchanger in which a fluid undergoes a liquid-to-vapor phase change.

external receiver - an exposed heat receiver, typically cylindrical in shape. In this type of receiver, tubes containing the heat transfer fluid are on the outer surface of the receiver and directly absorb the radiant energy.

field experiment - the construction and testing of a solar energy system in an actual operating situation.

flat-plate collector - a non-concentrating device that collects diffuse and direct solar radiation.

flux (radiant) - the time rate of flow of radiant energy.

flux density - the radiant flux incident per unit of area.

generator - a machine that converts mechanical energy into electrical energy.

heat exchanger - a device that transfers heat from one fluid to another.

heat pipe - a passive heat exchanger employing principles of evaporation and condensation to transfer heat effectively.

heat transfer fluid - the fluid circulating through a receiver that absorbs the sun's heat.

heliostat - a device for reflecting light from the sun in a desired direction. A typical heliostat may consist of a number of flat (or slightly concave) mirror facets mounted to a drive mechanism capable of pointing the mirror array in any desired direction, usually onto a fixed receiver.

hemispherical bowl collector - a stationary, bowl-shaped, solar thermal collector that concentrates radiant energy onto a movable linear receiver.

hybrid system - an energy conversion system that can be operated from solar energy or fossil fuel either interchangeably or simultaneously.

insolation - the solar radiation available at the Earth's surface. The maximum energy rate is about 1000 watts per square meter (100 watts per square foot).

linear (line)-focus receiver - a receiver that absorbs reflected radiant energy along a line of focus.

module - (1) unit consisting of a concentrator with support structure, receiver, and power conversion equipment. It can stand alone or be clustered with others to provide greater power capacity; (2) a self-contained unit that performs a specific task or class of tasks in support of the major function of the system.

molten-salt solar thermal system - a solar thermal system that uses molten nitrate salt, a heat transfer fluid, to store thermal energy.

organic Rankine-cycle engine - same as a Rankine-cycle engine, (see Rankine-cycle engine), except that the working fluid in the cycle is an organic compound instead of water/steam.

parabolic dish collector - a paraboloidal dish-shaped, dual-axis-tracking solar thermal concentrator that focuses radiant energy onto an attached point-focus receiver or engine/receiver unit.

parabolic trough collector - a paraboloidal trough-shaped, single-axis-tracking solar thermal concentrator that focuses radiant energy onto an attached linear-focus receiver.

peak watt - unit used for the performance rating of solar-electric power systems. A system rated at one peak watt delivers one watt at a specified level of insolation.

point-focus receiver - a receiver that absorbs reflected radiant energy at a point of focus.

power tower - a popular term used to describe a solar thermal central receiver system.

process heat - heat energy used in agricultural, chemical, or industrial operations.

Rankine-cycle engine - a closed-loop heat-engine cycle using various components, including (1) a working fluid pumped under pressure to a boiler where heat is added, (2) a turbine where work is generated, and (3) a condenser used to reject low-grade heat to the environment. The thermodynamic cycle upon which water/steam turbines are based.

receiver - see absorber

repowering - the retrofitting of existing fossil-fueled utility or process heat power plants with solar energy collection systems to provide the capability to displace a portion or all of the fossil fuel normally used.

retrofit - the installation of solar energy systems in already existing structures or facilities.

salt-gradient solar pond - a pond of stratified water that collects and retains heat. Convection, normally present in bodies of water, is suppressed by imposing a stable density gradient of dissolved salts.

single-axis tracking ability - the capability of moving in one direction, e.g., in an east-west direction.

solar energy - energy, in the form of radiation, emitted from the sun and generated by means of a fusion reaction within the sun.

solar furnace - a solar device used to obtain extremely high temperatures (over 2760°C, 5000°F) by focusing the sun's rays onto a receiver.

solar thermal electric conversion - the conversion of solar energy to thermal energy, which in turn powers a turbine/generator to produce electricity.

solar thermal energy systems - systems that utilize heat produced from the sun's rays to produce mechanical power, electrical power, or process heat.

Stirling-cycle engine - an external-combustion engine using pistons driven by heated gas. The gas travels in a sealed system from a receiver to the cylinders. It is potentially more efficient than a steam engine or gas turbine.

storage-coupled - the utilization of an energy storage system to permit operation of the end-use system during periods when solar power from the receiver is inadequate (or not present) to satisfy the load.

sunfuels - transportable fluids that are produced from either non-renewable or renewable resources, using energy from the sun in the synthesis process.

thermal energy storage system - any rechargeable unit capable of storing thermal energy for later use. Examples are storage as sensible heat in nitrate salt, oil, sodium, rock, water, or soil.

thermochemical conversion process - any process which transforms an initial set of chemical reagents into a different product set of chemicals involving the application or deletion of heat energy.

thermocline storage - the storage of thermal energy where the hot and cold media are in the same container (tank) using the thermocline principle which relies on a lower density hot fluid floating atop a



higher density cooler fluid of the same type, or which relies on hot solid material being separated from cooler solid material by a thermal gradient as in air/rock, air/ceramic brick applications.

total energy system - an energy system that uses waste heat from the generation of electricity to satisfy additional energy needs, e.g. electrical, heating, and/or cooling requirements.

tracking system - the motors, gears, and actuators instructed by computer command to maintain a proper orientation with respect to the sun and receiver positions.

turbine - an engine or machine driven by the pressure of steam, water, air, etc., against the curved vanes of a wheel or set of wheels fastened to a drive shaft.

working fluid - a pressurized fluid used to do work, e.g., drive a turbine; the pressurized working fluid in some systems is heated by passing through a heat exchanger from which it absorbs heat from a heat transfer fluid.

## APPENDIX B

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## APPENDIX C

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